STUDY OF FACTORS THAT

INFLUENCE PREDICTION OF CO_2 MMP

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STUDY OF FACTORS THAT INFLUENCE PREDICTION OF CO_2 MMP

By

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Dissertation submitted to the department of

Geoscience and Petroleum Engineering

in partial fulfilment of the requirements for

MSc degree in Petroleum Engineering

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CERTIFICATION OF APPROVAL

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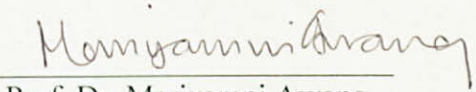

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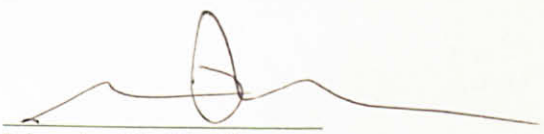

Iskandar bin Dzulkarnain

DEDICATION

To my beloved wife, Norashikin Mohd Said, our children, Mushab Irfan Al Khair and Wafa Azkia, and my parents, Dzulkarnain Abdullah and Rashidah Ismail. May God bless us all.

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My gratitude goes to Dr Mariyamni Awang for believing in my research potential. Thank you for the insight and guidance throughout the entire project. I also want to acknowledge my wife for all the moral and emotional support given in the course of completing this work. My heartfelt appreciation to Mr. Lutfi Bidin of PMU Petronas who helped me get out of the rough spots when the time gets tough. Lastly, to all who have assisted in the completion of this work directly and indirectly, may God reward you.

ABSTRACT

Prediction of minimum miscibility pressure (MMP) in miscible gas enhanced oil recovery (EOR) simulation depends on the ability of the equation of state to represent adequately the properties of components in the injected gas and oil mixtures over a wide range of conditions. Inaccurate description of the properties will undermine the predictive ability of the EOS model. The EOS can be used to calculate the MMP by two methods: numerical and analytical. Numerical methods involve 1-D slim-tube simulation and mixed-cell simulation. Analytical method utilises the key tie-line length algorithm.

The purpose of this work aims to understand the factors which affect the calculation of MMP for pure CO_2 injection using analytical EOS method. Since the method requires accurate characterization of the reservoir fluid, different selection of EOS, different selection of the PVT properties to match and the different selection of EOS variables to adjust may give different prediction of MMP. Proper treatment of these factors will reduce the inaccuracy of the MMP calculation from the EOS model.

In this work the factors are studied by looking at three aspects: 1) the selection of EOS, 2) the necessary PVT properties that the EOS need to match in order to predict the MMP accurately, and 3) the tuning strategies which are employed to match the EOS model with the PVT data for subsequent calculation of MMP.

This work attempts to investigate these factors by the following approaches: 1) comparison of available EOS's in a commercial PVT package and their performance when calculating MMP, 2) tuning the EOS to match selected PVT data and observing the predicted MMP from the tuned EOS, and 3) comparison of different tuning strategies proposed in the literature to tune the EOS to match the experiment data and evaluating the tuned EOS

calculation of MMP. The selected EOS's for comparison study are PR Peneloux and SRK Peneloux. For the matching PVT property study, the EOS model is tuned to match the solution gas/oil ratio (GOR), the liquid phase density and the oil formation volume factor (FVF). In the tuning variables study, two different tuning procedures are compared.

The results show that for a pure CO_2 miscible gas injection scenario, the SRK Peneloux EOS can be used to obtain acceptable MMP prediction. Besides matching the saturation pressure accurately, matching the density is also required. It is also shown that using the tuning variables such as critical temperature T_c, critical pressure P_c, acentric factor and the volume shift parameter can better tune the EOS for accurate prediction of MMP.

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CHAPTER 1: INTRODUCTION

1.1 General Background and Motivation

Malaysia oil reserves were declining prior to 2002 but the trend is reversed with the discovery of deepwater fields. However, without any new reserves addition and with the current rate of production, the reserves will be depleted within 19 years (Samsudin et al., 2005). In a matured exploration and producing area such as Malaysia, enhanced oil recovery (EOR) implementation is one of the ways identified to increase oil recovery. EOR screening studies conducted by PETRONAS to identify EOR potential in Malaysia indicated that about 1 Bstb additional crude oil could be recovered from Malaysian producing fields through application of EOR. It also identified miscible CO_2 as the most amenable process (Zain et al., 2001).

Among the aims in the design of CO_2 miscible process is to determine the operating condition where it is sufficient for miscibility to occur between the reservoir fluid and injection gas. The percentage of recovery increases when both fluids achieve miscibility. First contact miscible (FCM) develops when the fluids are miscible in all proportions. However, it is rare to find reservoir conditions that are suitable for first contact miscible process as the pressure is usually very high than usual reservoir pressure. Miscibility may also occur through repeated contact with the reservoir fluid in a multi-contact miscible (MCM) process. For design considerations, it is important to determine the minimum miscibility pressure (MMP) of the MCM process.

The reason for determination of MMP is that there is a balance between achieving high recovery and reducing production costs (Ahmed, 2007). If the injection pressure is too low, the displacement would be two-phase immiscible. If the pressure too high, the cost of pressurizing the injected gas would increase even though miscibility is achieved.

Slim tube experiment is conducted to determine the MMP. However to model the interaction of flow and phase behaviour of injection gas into a reservoir, a fully compositional simulation is required. The simulation can predict recovery and multiple development scenarios for economic analysis. A disadvantage of fully compositional simulators is that they require accurate fluid characterization by equations of state (EOS) to model the phase interaction in miscible gas process (Ahmed, 2007) .

Furthermore, the calculation is time-consuming and CPU-intensive depending on the EOS fluid characterization method for the particular EOS. Before the characterized fluid is used in compositional simulation, it is usually recommended to perform PVT simulations and compare with measured PVT data. Regression or EOS tuning is performed so as to minimize the difference between predicted and measured values (Ahmed, 2007) .

However, if the tuning parameters of EOS were adjusted excessively to match the PVT data, it would lead to unrealistic results. This is known as over tuning of EOS. As discussed by Pedersen, Thomassen, and Fredenslund (1988), over tuning may happen if the fluid is characterized with heavy lumping and this can be avoided by proper compositional analysis and characterization of reservoir fluid. Therefore, to obtain a satisfactory prediction of PVT data requires careful judgement on the part of the engineer and multifarious interplay between the choices of EOS, the fluid characterization method to be used, the selection of EOS parameters to be regressed and the fluid properties to be matched. Nevertheless, it comes as no surprise that the process of obtaining a match between the EOS model and actual PVT data is regarded as more art than science.

With regard to MMP prediction from EOS, numerous authors have done studies on the methods to perform the analytical calculations of MMP faster and more efficient. Wang (2000) and Jessen, Michelsen, and Stenby (1998) have introduced algorithm using key-tie line approach that minimise the time for MMP calculation. Comparison studies have also been done to evaluate which MMP experiments could determine the MMP better. Ayirala, Rao, and Casteel (2003) compared the Vanishing Interfacial Tension (VIT) method with EOS prediction and concluded that VIT gives acceptable match with EOS calculation. Similarly, Jessen and Orr (2007) compared the VIT method with slim tube experiment and EOS prediction and concluded that the former is less accurate and reliable as it does not create the critical mixtures necessary for miscibility to develop.

1.2 Problem Statement

The purpose of this work aims to understand the factors which affect the calculation of MMP for pure CO_2 injection using analytical EOS method. Since the method requires accurate characterization of the reservoir fluid, different selection of EOS, different selection of the PVT properties to match and the different selection of EOS variables to adjust may give different prediction of MMP. Proper treatment of these factors will reduce the inaccuracy of the MMP calculation from the EOS model.

1.3 Objectives

The aim of this work is to analyse the effect of EOS selection, tuning parameters selection and selection of matching fluid properties on the EOS prediction of purely CO_2 MMP. The justifications are given below:

1. To select EOS for pure CO_2 MMP prediction

   Stalkup and Yuan (2005) studied the effect of having two different EOS model; both using PREOS and both gave acceptable matching of the same PVT data but differed on the prediction of MMP. They

concluded that achieving a satisfactory prediction of PVT data with an EOS does not necessarily imply that the EOS predicts the MMP very well. The conclusion is reached for the PREOS with miscible displacement using mixture of methane and nitrogen. Does it apply to the SRKEOS as well? What if the miscible displacement is pure CO_2?

2. To select matching PVT data in the regression

   Ayirala, Rao, and Casteel (2003) compared MMP from VIT and EOS calculation and noted that in spite of matching the saturation pressures with acceptable changes in EOS parameters, significantly different MMP predictions for different tuning processes are obtained. They suggested the possibility of choosing another measured property to match other than saturation pressure in MMP prediction.

3. To select regression strategy

   Coats and Smart (1986) proposed using five variables of methane Ω_A and Ω_B, plus fraction Ω_A and Ω_B, and the methane – plus fraction binary interaction coefficient (BIC) of the Peng-Robinson EOS (PREOS). (Christensen, 1999), on the other hand suggested using the volume translation parameter in the plus fraction and two most sensitive coefficients among T_c, P_c and ω of the Soave-Redlich-Kwong EOS (SRKEOS). Pedersen, Christensen, and Azeem (2006) noted that the practice of tuning binary interaction coefficients (BIC) to match saturation pressures might not always be necessary, even though it is sometimes effective. All in all, there are no consistent variables to tune to match PVT data and more so MMP.

1.4 Scope of Work

Furthermore, in order to focus on the questions, the scope of the work is limited to the study on fluid parameters matching, EOS selection and influence of regression parameters on the MMP prediction. The work will not attempt to explore the effect of fluid characterization and pseudo-component selection in

predicting MMP. Apart from that, the EOS selection is limited to PR Peneloux EOS and SRK Peneloux EOS. The choice of the pseudo-components is limited to 5 pseudos for a total of 15 components and the characterization method is based on Pedersen, Christensen, and Azeem (2006).

1.5 Thesis organization

This thesis is organized into five chapters, including this introduction chapter.

Chapter 2 describes the extensive background on this thesis. The miscibility process, miscible drive mechanisms, methods for estimating MMP and EOS fluid characterization, especially overview of reservoir fluid analysis, pseudo-component selection and tuning process are introduced.

Chapter 3 focuses on the methodologies and assumptions used to approach the research questions.

Chapter 4 presents detailed description of the results obtained, followed by discussions, analysis, and interpretations of the data obtained.

Chapter 5 summarises the analysis and findings from the data as well as suggestions for future work.

CHAPTER 2: LITERATURE REVIEW

2.0 Chapter Overview

The process of miscible gas injection into reservoir often requires compositional simulator to model the complex phase behaviour. In order to make useful prediction, the EOS model used must be characterized accurately. Several researchers (Pedersen, Christensen, and Azeem, 2006), (Whitson, 1983), and (Rafael A. & William D., 2002) have done extensive work to develop fluid characterization methods. Characterizing reservoir fluid is a tedious work requiring insight and experience. Several questions need to be pondered to achieve the necessary EOS characterization required in the compositional simulation. The rest of this chapter will build the foundation of the research work by addressing the following questions:

1. How miscibility develops during gas injection in the reservoir?
2. What kind of phase behaviour will result from the interaction of the oil and injected gas at the prevailing reservoir condition?
3. What is the driving mechanism of the miscible process?
4. How to estimate the MMP for the reservoir?
5. How to characterize the reservoir oil?
6. What tuning approach will be applied to determine the EOS fluid properties?

2.1 Development of miscibility and drive mechanism

When subjected to favourable conditions of pressure and temperature, together with suitable oil composition, CO_2 can achieve miscibility with reservoir oil. This help to remobilize and produce residual oil trapped due to interaction between capillary pressure and interfacial tension. Entrapment and movement of fluid in porous medium is known to depend on the pore structure of the reservoir, fluid/fluid interaction (due to interfacial tension (IFT) and mobility), and fluid/rock interaction (influenced by wettability). By injecting CO_2, miscibility is achieved by reducing the IFT toward its lowest value. Apart from that, injection of CO_2 also reduces the viscosity and increases the swelling of the oil. Viscosity reduction is often accompanied by small increase in water viscosity which further reduces the water-oil mobility ratio. Swelling of the oil increases the recovery factor since, for a given residual oil saturation, the mass of the oil remaining in the reservoir and expressed in standard conditions is lower than if the abandoned oil was CO_2 free.

Metcalfe and Yarborough (1979) classify CO_2/reservoir fluid phase behaviour into two broad types according to the characteristics of the pressure/composition diagram. At temperatures above 120□ F, vapour and liquid phases coexist. This forms the basis for most fluid characterization PVT data. However, when the temperatures below 120□ F, phase behaviour is more complex because some mixtures separate into equilibrium vapour and liquid phases, while others separate into two coexisting liquid phases and also three coexisting phases consisting of two liquids and a gas. (Campbell and Franklin M., 1985) did a study of phase behaviour of CO_2/crude oil at low temperatures and concludes that the transition temperature from one phase to the other is influenced by the average molecular weight of the oil. In slim-tube simulation, knowledge of the phase behaviour of the particular gas/oil system will help to determine the sensitivity to numerical dispersion in that system (Jessen, Stenby & Franklin M., 2002).

Miscible displacement by CO_2 is often a multi-contact process. Repeated contacts between oil and injected gas allow mass transfer of components which result in vaporisation or extraction of heavier hydrocarbons (C5 – C30) from the oil and concentrate them at the displacement front where miscibility is achieved. Besides CO_2, multi-contact miscible displacements often involve the injection of N_2, CH_4 or a mixture of hydrocarbon gas.

These solvents do not mix directly with the oil and often form two phase upon contact. It is possible to achieve first contact miscibility where the gas mixes with the oil completely, in all proportions, such that all mixtures are single phase. This can be done by injecting solvents with intermediate-molecular-weight hydrocarbons, such as propane, butane and mixtures of liquid petroleum gas (LPG).

However, the pressure required is often greater than the reservoir pressure and the cost involved may offset the benefit as the solvent used is too expensive to be injected continuously. Instead, the solvent is injected in a limited volume, or slug, that was small relative to the reservoir pore volume, and the slug in turn is miscibly displaced with a less expensive fluid such as natural gas or flue gas.

In actual displacement process, multi-contact miscibility (MCM) occurs through pure vaporising or combined condensing-vaporising drive (CV) mechanism. To represent the process, pseudoternary diagram is usually used. Based on the ternary diagram, the displacement is MCM if either the injected gas composition (condensing drive) or the oil composition (vaporising drive) is located outside the region of tie-line extensions. During condensing drive, rich gas (richer in intermediate components than the oil) is injected and some of the intermediate components are absorbed by the oil and the oil became lighter as more gas flowed through it. Similarly, when lean gas (such as CO_2) is injected, some of the intermediates in the oil are vaporised into the gas.

Many of the earlier methods to estimate MMP were based on simplifications or derivations of the pseudoternary representation of the compositional space. Studies done by Zick (1986) and Stalkup (1987) have

shown the existence of condensing- vaporising drive (CV) mechanism. With these findings, new methods were developed to account for the CV drive mechanism using effective algorithms. The new methods have superseded the earlier methods as the latter fail to honour the existence of a combined mechanism controlling the development of miscibility in real reservoir fluids.

2.2 Methods for estimating MMP

Currently there are three methods to determine MMP: experimental approaches, correlations and equation of state (EOS) techniques. Experimental methods include slim-tube tests (Wu and Batycky, 1990), rising bubble apparatus (RBA) (Mihcakan, 1994) and vanishing interfacial tension (VIT) technique (Rao and Lee, 2000). Numerous correlations to estimate MMP based on the regression of slim-tube data were developed for screening purposes (F.M. and Silva, 1987; F.M. and Jensen, 1984; Glaso, 1980; Yuan et al., 2004). Some of these correlations were used in predicting MMP's of pure and impure CO_2 while others treat the MMP's of all other type of gases. EOS methods can be further categorised into numerical methods and analytical techniques. Numerical methods employ mixing cell models (Ahmadi and Johns, 2008) and 1-D compositional simulations (Metcalfe et al. 1973). Latest developments (Wang, 2000; Jessen, 1998; Hua and Johns, 2002) apply the analytical techniques to calculate MMP's for dispersion-free displacements. The advantages and drawbacks of each method are discussed in this section.

2.2.1 Experimental Methods

The primary experimental methods to evaluate miscibility under reservoir conditions are the slim-tube displacement and the rising bubble apparatus. Slim-tube method is the most common and has been accepted as the standard method to determine MMP. The apparatus (Stalkup, 1983) is made up of a coil usually 20-200 ft long packed with sand or glass beads. The tubing for the coil has a small diameter to ensure the displacement is approximately one-dimensional (1-D). The tube should be long enough for transitional mixing of

MCM flow to take place. The permeability of the slim-tube apparatus is very high so that the whole process remains approximately at constant pressure. The miscibility conditions are determined by conducting the displacements at various pressures or gas enrichment levels and monitoring the oil recovery. Then, the oil recovery is plotted against the pressure. The minimum miscibility pressure is defined as the pressure at which the oil recovery vs. pressure curve shows a sharp inflection. Extremely low flow rates, long lengths and smaller diameter tubing are preferred to avoid the unfavourable effects of fingering, transition zone length and transverse compositional variations. Hence, it is very time consuming and may take several weeks to complete the measurements.

Furthermore, there is neither a standard design, nor a standard operating procedure, nor a standard set of criteria for determining the MMPs with a slim-tube (Elsharkawy, Poettmann and Christiansen, 1992). Several different criteria are used, among the well-known are:

- Oil recovery of 90% at 1.0 pore volume (PV) of gas injected.
- Oil recovery of 90% at 1.2 PV gas injection.
- Oil recovery of 95% at gas breakthrough or more than 80% at gas breakthrough.
- Oil recovery of 94% when the gas-oil ratio (GOR) reaches 4000 scf/bbl.
- Distinct point of maximum curvature when cumulative recovery of oil at 1.2 PV gas injected is plotted against pressure.
- Distinct point of maximum curvature when recovery of oil at gas breakthrough is plotted versus pressure.

The non-unique nature of the criteria leads to uncertainty in the estimation of MMP.

In the rising bubble (RBA) experiment, the MMP is inferred from the pressure dependent behaviour of rising bubbles. The MMP is determined from the observations of changes in shape and appearance of bubbles of the injected gas as they rise through thin column of crude oil. This method is considerably faster and cheaper and requires smaller quantities of fluids, compared to slim-tube. However, the interpretation is subjective in nature and little quantitative information (composition changes, interfacial tension and displacement efficiency) can be obtained (Elsharkawy, Poettmann and Christiansen, 1992). Zhou and Orr F. (1998) have shown that RBA is suitable for predicting MMP's for vaporising drives but not CV drives. MMP estimates obtained by this method are also prone to experimental errors. Therefore there exists the need for laboratory measurement to determine MMP quickly and accurately, while being quantitative.

Recent laboratory method was developed which involves measuring the interfacial tension between the injected gas and crude oil at reservoir temperature under varying pressures or enrichment levels of gas phase. The method is based on the concept that at miscibility, the interfacial tension between the two phases (injected gas and crude oil) is zero (Rao and Lee, 2000). The MMP is determined by extrapolating the plot between the interfacial tension and pressure to zero interfacial tension. However, the method may not be reliable as it lacks the proper interaction of flow with phase behaviour required to achieve multi-contact miscibility (Jessen and Orr, 2007).

2.2.2 Correlations

Correlations to determine MMP is based on the regression fit on slim-tube experiment data. To facilitate screening procedures and gain insight into the miscible displacement process, many correlations relating the MMP to the physical properties of the oil and the displacing gas have been proposed. Ahmed (2007) highlighted that any MMP's correlation should satisfy the following criteria:

- Account for each parameter known to affect the MMP.
- Be based on thermodynamic or physical principles that affect the miscibility of fluids.
- Be directly related to the multiple-contact miscibility process.

Although less accurate, these correlations are quick and easy to use and generally require only a few input parameters. Hence, they are very useful for a fast screening of a reservoir for various types of gas injection. They also are useful when detailed fluid characterizations are not available. One significant disadvantage of current MMP correlations is that the regressions use MMP's from slim-tube data, which themselves are uncertain. Some MMP correlations require only the input of reservoir temperature and the API gravity of the reservoir fluid. Other, more accurate, correlations require reservoir temperature and the total C_2–C_6 contents of the reservoir fluid.

Recent development (Yuan et al., 2004) utilised analytical theory for MMP calculations from EOS to generate MMP correlations for displacements by pure or impure CO_2. The correlation requires reservoir temperature, molecular weight of C_{7+}, and percentage of intermediates (C_2-C_6) in the oil. Yuan et al. (2004) compared the correlation with experimentally measured MMP's and concluded that it can reduce error due to slim-tube uncertainty in MMP calculation for a diverse range of reservoir fluids and temperatures.

2.2.3 Equation of States Methods

EOS methods to predict MMP can be categorised further into numerical methods and analytical techniques. Numerical methods involve the application of 1-D compositional simulation and mixing cell simulation. Analytical techniquess use method of characteristics (MOC) approach to determine MMP. Overall, these methods share one thing in common: they require accurate EOS characterization of the fluid to calculate the MMP.

2.2.3.1 Numerical Methods

These methods to predict MMP include fine grid 1-D compositional simulations and mixing cell models. In the 1-D slim-tube compositional simulation, different grid-block sizes with relatively constant pressure are used to simulate the displacement process. The oil recovery at extrapolation to zero-dispersion (infinite number of grid-blocks) is estimated for each pressure and a plot of recovery versus pressure is made. The MMP is estimated as the pressure at the point of maximum curvature of the curve. The MMP determined from this method is affected by numerical dispersion if coarse grids are used in the simulation. Consequently, to obtain a better estimate, finer grids should be used but this will prolong the simulation time. Numerical dispersion occurs due to truncation error when partial differential equations approximations are used to represent the displacement process.

Multiple mixing-cell models were first proposed by Metcalfe et al. (1973) and have been used to explore the mechanism of multi-contact miscible process. It is a discrete model of a continuous gas injection process in the slim-tube experiment. The models are run with forward and reverse contacts flash calculations. Repeated contacts for a mixture of equilibrium oil and gas injection (reverse contact) or a mixture of equilibrium gas and reservoir oil (forward contact) are calculated for a purely condensing or purely vaporising drive. The MMP is calculated to be the pressure at which the mixture becomes single phase (i.e. the gas or oil tie line becomes the limiting tie line at the critical point). A drawback with this method is that the calculations assume a purely condensing or vaporising drive, hence it cannot account for the effect of CV drive displacements. Furthermore, it is also susceptible to numerical dispersion and accurate MMP calculation can be obtained by refining the cell blocks.

Recently (Ahmadi and Johns, 2008) have developed an improved mixing-cell method that can mitigate the effect of numerical dispersion yet simple and reasonably fast using variable number of cells and relies on robust P-T flash calculations with any EOS.

2.2.3.2 Analytical Techniques

Analytical techniques using key tie-line based on method of characteristics (MOC) were developed by Hua and Johns (2002); Jessen, Michelsen and Stenby (1998); Wang and Orr M. (1998) to calculate MMP more accurately. Their work have shown that three types of key tie-lines control the development of miscibility in a multicomponent system, namely (i) the tie-line extending through the initial oil composition; (ii) the tie-line extending through the initial injected gas composition; and (iii) series of crossover tie-lines which has a point of intersection with tie line (i) and tie-line (ii). In a purely condensing or a purely vaporising drive, the displacement miscibility is controlled by tie line (i) and tie-line (ii) respectively. For a CV drive, miscibility is controlled by one of the crossover tie-lines. The MMP is determined once these key tie-lines are found for a given pressure by extending the pressure in steps until one of the key tie-lines becomes the critical tie-line (i.e. the tie-line length's becomes zero as it intersects the critical locus).

Besides speed and accuracy, the main advantage of this method is that the estimated MMPs are independent of dispersion. However, the method still needs to address the difficulties in determining intersection of tie-lines corresponding to compositions that are close to identical and handle miscible gas displacement with three-phase flow (LaForce and Johns, 2005).

2.3 Equation of State Fluid Characterization

Petroleum reservoir fluids contain several hundred different components, which are impossible to be handled by EOS models. The components can be categorised into two categories: the well-defined components and the undefined petroleum fractions, which are the heavy compounds collectively grouped together and called the plus-fractions (i.e C_{7+}). The physical properties of the defined components are well understood. The critical temperature (T_c), critical pressure (P_c), and acentric factor (ω) for each defined component required by the EOS model are readily available (Dandekar, 2006).

However, for the plus-fractions the physical properties available are usually the mole fraction (MW), and specific gravity (SG). It is difficult, if not impossible, to obtain the critical properties experimentally. Therefore the fluids need to be characterized accurately for the EOS models to be able to simulate and predict the phase behaviour and physical properties of the reservoir fluids over a wide range of conditions. Characterization of the plus-fractions usually involves the following steps (Peng and Pope, 2001):

1. Splitting the fractions into a certain number of component groups called single carbon numbers (SCNs);
2. Estimation of the psycho-chemical properties of the SCN by use of empirical correlation;
3. Lumping of the generated SCNs into several pseudo-components;
4. Calculation of the pseudo-chemical properties of these pseudo-components by use of mixing rule.
5. Validation of EOS model against experimental PVT data to determine whether tuning of the EOS parameters is required.
6. Tuning of the EOS model by selecting suitable experimental data to tune to and selecting adjustable EOS parameters to be used to match these data.
7. Evaluation of the predictive capability if the EOS model.

2.3.1 Characterization Process

Reservoir fluid analysis from True Boiling Point distillation (TBP) will usually give the fluid composition up to C_{20+}. Furthermore, compositional analysis up to C_{30+} is possible. However, it is time consuming and difficult analysis as the process conditions are not easily manipulated (Dandekar, 2006). TBP compositional analysis is preferred in the industry compared to Gas Chromatography (GC) as the latter lack pertinent information such as the molecular weight and the specific gravity of the SCN groups required to convert the mass fraction to molar basis required for compositional analysis (Danesh, 1998).

Plus-fractions in the fluid compositions (C_{7+}, C_{12+}, and C_{30+}) are further split into SCN groups. This is because insufficient description of the plus-fractions will undermine the accuracy of the PVT predictions (Whitson, 1983). Furthermore, it is unlikely for any EOS model using a single component for such plus-fractions to adequately model the phase behaviour of the fluid, even with tuning. The splitting methods use distribution functions that honour the measured MW and SG. Several such methods were developed by Pedersen, Christensen and Azeem, (2006) and Whitson and Brule (2000)

To estimate properties of these SCN groups, correlations such as those proposed by Twu (1984), (Whitson, 1984) and Ahmed (2007) are used. These correlations are in principal function of the MW, SG and the boiling point temperature (T_b). The properties estimated by these correlations (T_c, P_c and ω) are required by the EOS model to run simulation and prediction of the phase and volumetric behaviour of the fluid.

The SCN groups are then grouped or lumped together into several pseudo-components to reduce the computation time and storage requirement during simulation. The optimal number of pseudo-components depends on the nature of the reservoir study. A detailed multi-component model (say 24 components) may be necessary to study displacement processes in more detail in a limited section of the reservoir at the pattern scale while a few components could be more applicable for field scale. Pedersen, Christensen and Azeem (2006) states that lumping consists of:

1. Deciding what carbon number fractions are to be lumped into same pseudo-component.
2. Deciding the mixing rules that will average T_c, P_c and ω of the individual carbon number fractions to one T_c, P_c and ω to represent the lumped pseudo-components.

Several methods for lumping components into pseudo-components and determining their EOS properties were proposed. The simplest methods assign pseudo-components based on component mole fractions (Cotterman and Prausnitz, 1985), mass fractions (Pedersen, Rasmussen & Fredenslund, 1985),

ranges in molecular weights (Whitson, 1983) and K-values (Newley & R.C., 1991).

To extend the use of EOS to pseudo-components mixtures, mixing rule is used. The mixing rule can be employed to characterise the pseudo-components in terms of its pseudo-physical and pseudo-critical properties. The selection of the mixing rule is as important as the lumping scheme since poor selection may result in significant change in the phase behaviour predictions. Some of these mixing rules are proposed by Hong (1982) and Leibovici, Govel and Piacentino (1993).

2.3.2 Tuning Process

The critical properties assigned to the pseudo-components may not reflect the actual phase behaviours from the EOS model predictions. One of the reasons is that the properties are only estimates based on the empirical correlations and mixing rules used. Consequently, the correlations and the mixing rules introduce some uncertainties and errors in the model predictions. Apart from that, excessive pseudo-izations may be necessary in some compositional simulations and it often deteriorates the quality of the simulations to some extent (Pedersen, Christensen & Azeem, 2006). Therefore to mitigate this problem, the parameters in the EOS model are tuned to achieve satisfactory match with the PVT data. The experimental data used should be closely related to the reservoir fluid and the recovery process implemented in the field. Typical PVT data used for tuning include:

- Differential depletion test
- Constant composition expansion test
- Swelling test
- Constant volume depletion test
- Multiple-contact test

- Separator test

EOS tuning is usually performed using manual adjustments through trial and error or by multivariate, non-linear regression tool. The tuning variables are selected to achieve a match between the experiment and EOS model. Peng and Pope (2001) recommended using the critical properties (T_c, P_c, and ω) of the plus fractions as the tuning variables. Coats and Smart (1986) proposed adjusting the Ω_A and Ω_B of the plus fractions. Although tuning the variables are necessary to achieve matching, (Pedersen, Thomassen & Fredenslund, 1988) cautioned against excessive tuning, where the variables are adjusted beyond the limits of physical behaviour as it may introduce unrealistic results. Apart from that, not all properties in the PVT data need to be matched accurately. Certain properties such as saturation pressure and density are more emphasised than the other properties such as the Z-factor and relative volume. Toward this end, Coats and Smart (1986) recommended a set of weight factors which are assigned to each property based on its accuracy and measurement reliability.

Several procedures have been suggested to perform tuning of EOS model (Al-Meshari and McCain, 2005; Christensen, 1999; Rafael A. and William D., 2002). Tuning to match PVT data is regarded as more art than exact science as there are a variety of procedures for tuning. (Peng & Pope, 2001) suggested categorizing the measured experimental data into phase-equilibrium data (saturation pressures and K-values), molar and volumetric data (molar and volume fractions, and molar volumes), MW-related data (mass density), and other data such as viscosity and IFT. Critical properties of the plus-fractions in the EOS model are used to match the phase equilibrium data and molar and volumetric data first. This is followed by matching the mass density by adjusting the MW and finally the viscosity by adjusting the critical volume.

Whatever procedure is followed, the properties of the defined components are not usually adjusted. The adjustments are done to the plus-fractions, which have the greatest level of uncertainty. Apart from that, the tuned EOS model will only be valid for the pressure and temperature range covered by the experimental data. It should be noted that with proper EOS characterization, a

reasonable guideline is to tune as few variables as possible and as little as possible to achieve acceptable match with the PVT data while maintaining the internal consistency among the parameters.

2.4 Chapter Summary

This chapter begins with the description of the miscibility process and the driving mechanisms, namely condensing drive, vaporising drive and CV drive. MMP prediction methods have to take into account the effect of these drive mechanisms. Methods to estimate MMP include experimental methods (slim-tube, RBA and VIT), correlations and EOS methods, which can be further categorised into numerical methods (slim-tube simulation and multiple mixing cells simulation) and analytical techniques. Correlations are generally used for screening purpose and more accurate MMP can be obtained through slim-tube experiments. However, the experiment has no standard procedure to evaluate the result and time-consuming. For compositional simulation studies, the MMP can be estimated through the EOS methods. These methods require accurate characterization of the fluid to obtain a reliable estimate. Furthermore, some of the methods suffer form numerical dispersion if coarse grids are used. The chapter ends with the description of the EOS characterization procedure beginning with the extended fluid analysis, compositions splitting and lumping and finally tuning process to match PVT data. The next chapter will describe the methodologies used in this research.

CHAPTER 3: METHODOLOGY

3.0 Chapter Overview

This chapter will describe the approaches taken in this research. The rest of the chapter will detail the experimental database used, fluid characterization method, tuning approach and MMP determination.

3.1 Experimental Database

In the open literature, the availability of comprehensive fluid data especially experimental MMP data is limited. Toward this end, Jaubert (2002) published a database (13 reservoir oils including their respective injection gases) consisting of the full compositional data, standard PVT experiments, swelling tests, and MMP determinations from slim-tube experiments. The data from sample JF_{13} is used in this study as the injection gas is purely CO_2. The fluid is medium oil with 35.2° API, saturation pressure of 171 bar, reservoir temperature of 377.55 K and slim-tube MMP 271 bar.

The compositional analysis is given up to $C20_+$ from the fractional true-boiling-point (TBP) distillation. Apart from that the specific gravity, molecular weight and the amount of each heavy components from C_7 to C_{19} including the amounts of TBP residual (C_{20+}) are also tabled.

3.2 Fluid JF_{13} Characterization

The characterization procedure by Pedersen, Christensen and Azeem (2006) was applied to obtain EOS model from the compositional analysis data of fluid JF_{13}.

Two case studies, one using Peng-Robinson Peneloux EOS (PREOS) and the other using Soave-Redlich-Kwong Peneloux (SRKEOS) were prepared to evaluate the MMP predictions. In the Pedersen, Christensen and Azeem (2006) method, molecular weight is related to the mole fraction through an exponentially decaying function which describes the quantity of fluid with respect to the molecular weight of single-carbon-number groups (i.e. discrete representation). Furthermore, the choice of pseudo-components representing the TBP cuts and the TBP residue is made by dividing the fluid into a number of pseudo-components representing equal mass fractions. The case studies were prepared using a total of 15 components (defined and pseudo-components).

The EOS characterization is performed through these five steps: 1) Base case fluid models (15 components) are prepared for the respective EOS's without tuning; 2) The base case is tuned using non-linear regression to match PVT data; 3) Comparison cases consisting of tuned base cases using tuning variables (T_c, P_c, ω, Ω_A, Ω_B, and k_{ij}) are prepared for each EOS; 4) MMP's are calculated using analytical method for each cases; and, 5) The models are analysed by comparing with the PVT data and experimental MMP data

3.3 Tuning Approach

The characterized fluid may not be sufficient to represent the experimental data accurately. Therefore, the EOS models need to be tuned by regression procedure to improve on the accuracy. In this research, the performance of the PREOS and SRKEOS are evaluated at two stages:

1. Pure prediction based on the default characterizations.
2. After regression of standard PVT measurements such as constant-mass-expansion experiments (CME) and differential-depletion experiments (DDE).

Tuning variables used in the regression procedure are listed below:

- The critical temperature T_c of the plus-fractions in the characterized fluid description.
- The critical pressure P_c of the plus-fractions in the characterized fluid description.
- The omega's (Ω_A and Ω_B) between methane and the plus-fractions of the characterized fluid description.
- The acentric factor ω in the plus-fractions of the characterized fluid description.
- The binary interaction parameter (k_{ij}) between methane and plus-fractions of the characterized fluid description

To reduce the degree of freedom when tuning the two base case EOS models to the PVT data, the tuning approach is limited to involve columns of pseudo-components. That is, for example, the column of critical temperatures (T_c) is adjusted for all pseudo-components by a common factor. Through this approach, the trends of the original fluid characterizations are improved. The critical properties are adjusted generally by less than 20 % while the binary interaction parameters may be adjusted to higher percentages. The regression module in PVTSim is shown in Appendix A.

Data regression is performed by using a standard Marquard-Levenberg algorithm. The experimental data (pressures, densities, and relative volumes) were assigned different weights in the regression process to reflect their relative importance. The weight factors were set to 50, 10, and 1 respectively for pressures, densities, and relative volumes as proposed by Coats and Smart (1986). PVTSim software is used for the tuning process.

3.4 MMP Calculation

MMP calculation is performed using the analytical method. Details of the steps for MMP calculations are shown in Appendix B.

3.5 Chapter Summary

The chapter gives a brief outline of the general framework of the research problem. Discussions about the fluid data, characterization method tuning process and MMP calculation are given. The next chapter will focus on the results obtained and discussions of the results.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.0 Chapter Overview

In this chapter analysis of the results are covered. It is shown that the better choice for EOS to predict CO_2 MMP analytically is SRK Peneloux. On the other hand, regarding the matching properties used in PVT data regression, it is observed that matching the EOS model to density data gives better MMP prediction. Aside from that, it is noted that the tuning variables suggested in Jessen and Stenby (2007) regression procedures would better match the experimental data and consequently give better MMP calculation.

4.1 Selection of EOS

Two EOS models, one using PR Peneloux and the second using SRK Peneloux were compared in the first part of this study. The base case models without tuning were characterized for both EOS's. Initially the compositional analysis with 30 components was splitted into 80 SCN's before lumping scheme was applied to group the model into 15 components. Next the average critical properties of the pseudo-components were calculated using the mixing rule as proposed by Christensen (1999). To facilitate calculation of MMP, each model was characterized with their respective injection gas using the same pseudo-components. Tuning of the model to match with saturation pressure and other PVT data were done by performing regression on constant

mass expansion (CME) data and differential liberation (DLE) data. Appendix C shows the critical properties of the 15-component model for the PR Peneloux characterization while Appendix D shows the properties of the SRK Peneloux model.

The two EOS models were compared based on their matching to the experimental saturation pressure, the general trend of matching with other PVT data and the predicted MMP. To obtain matching with saturation pressure, regression procedure by Jessen and Stenby (2007) was applied. Having too many tuning variables will undermine the predictive ability of the EOS. Therefore the degrees of freedom when tuning the two EOS models are reduced by restricting the tuning approach to involve only columns of pseudo-components.

Furthermore, since the heavier pseudo-components have large uncertainties in their critical properties after lumping, the tuning variables are limited to the T_c and P_c of these pseudo-components. Occasionally, in order to obtain a good match with the PVT data, the volume shift and the acentric factor are also used as tuning variables. Therefore, this results in a maximum of four adjustable parameters. The reason this approach is applied is to maintain the trends in the original fluid characterizations.

Tables 4.1 to 4.2 compare how well both models calculate the saturation pressure and MMP after tuning. Figures 4.1 to 4.6 show the match of the models to the experimental PVT data from CME and DLE tests.

To obtain a good comparison, all models were tuned to the saturation pressure. Therefore the weight factor for the saturation pressure points for both the CME and the DLE data were set to 50. In order to match the PVT data, the T_c and P_c of the C_{7+}, C_{13+}, C_{16+}, C_{20+}, and C_{57+} of the plus-fractions were adjusted by 20% respectively. The acentric factor and the volume shift parameter of the same pseudo-components were also adjusted by 20% and 50% respectively. These adjustments were the maximum changes allowable.

Table 4.1: Experimental and calculated fluid sample properties for PR Peneloux EOS model

	Psat	% Dev	Density at Psat	% Dev	FVF at Psat	% Dev	Rs at Psat	% Dev	MMP	% Dev
Experiment	171.00		722.60		1.250		101.6		271.00	
Initial	232.53	35.98	669.85	-7.3	1.391	11.2	111.4	9.7	264.64	-2.35
After Tuning	171.72	0.42	649.08	-10.2	1.842	47.3	208.4	105.1	247.96	-8.50
AAD		18.20		8.74		29.26		57.41		5.43

Table 4.2: Experimental and calculated fluid sample properties for SRK Peneloux EOS model

	Psat	% Dev	Density at Psat	% Dev	FVF at Psat	% Dev	Rs at Psat	% Dev	MMP	% Dev
Experiment	171.00		722.60		1.250		101.6		271.00	
Initial	243.19	42.22	672.80	-6.9	1.382	10.5	106.9	5.2	307.48	13.46
After Tuning	171.65	0.38	650.07	-10.0	1.846	47.6	207.7	104.4	256.76	-5.25
AAD		21.30		8.47		29.08		54.79		9.36

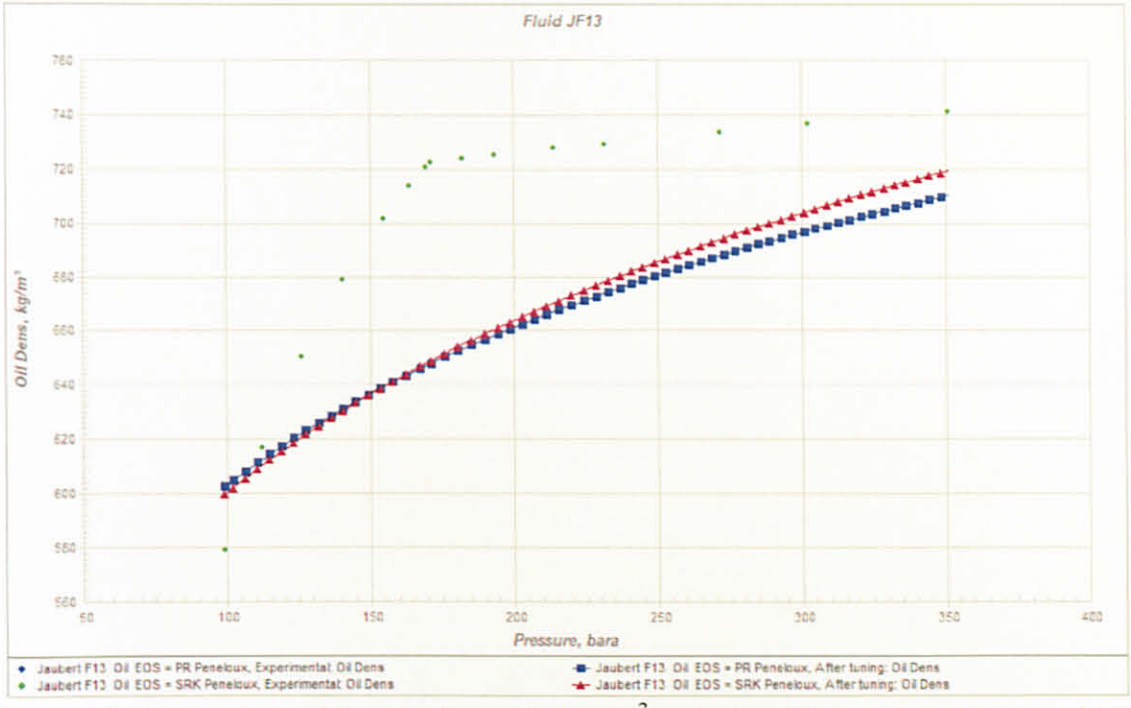

Figure 4.1: Comparison of CME oil density (kg/m^3) calculated by PR Peneloux and SRK Peneloux EOS model for fluid JF_{13} at 377.55 K

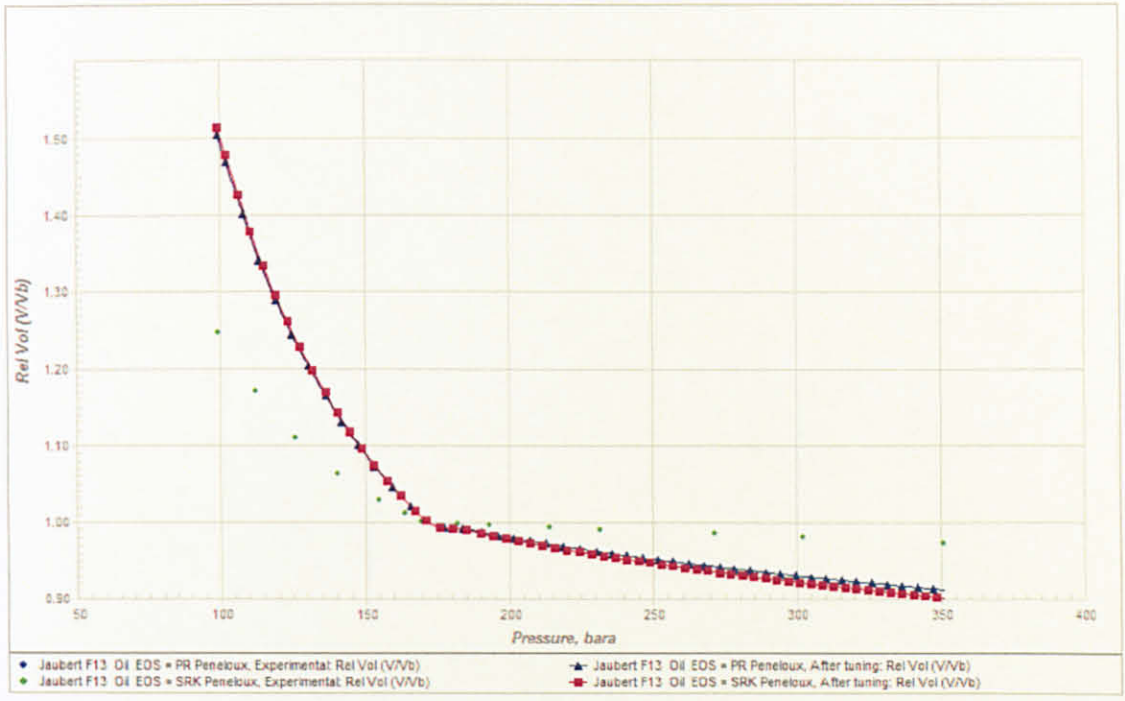

Figure 4.2: Comparison of relative volume (V/Vb) calculated by PR Peneloux and SRK Peneloux EOS model for fluid JF_{13} at 377.55 K

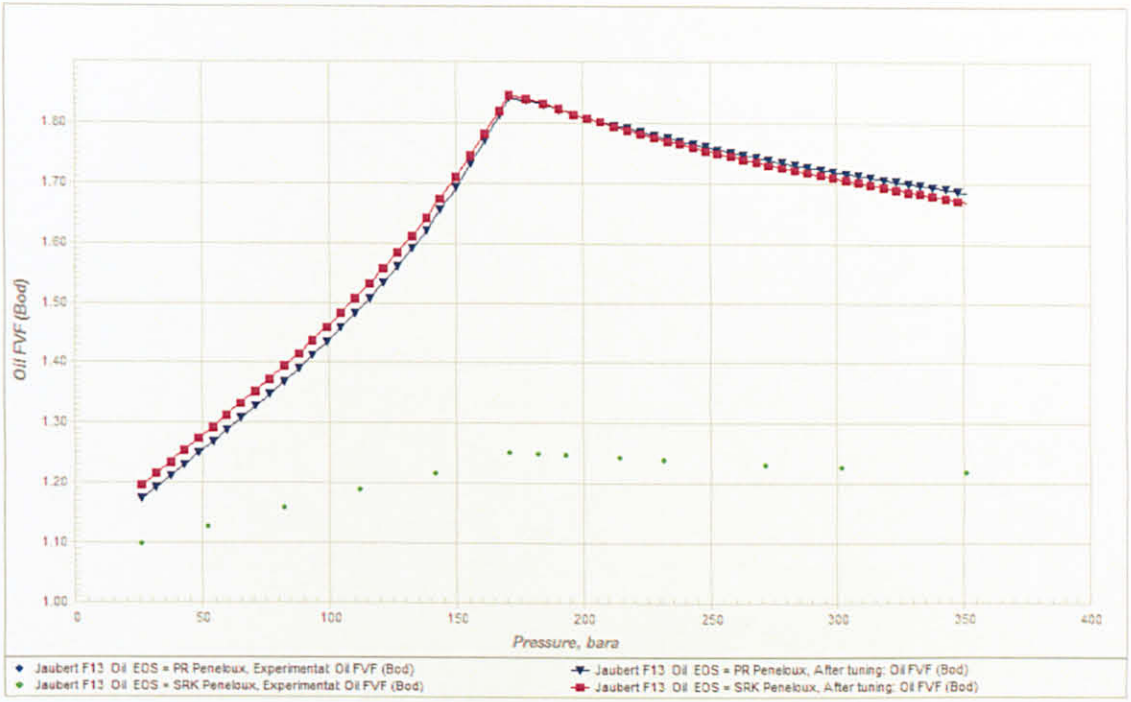

Figure 4.3: Comparison of oil FVF (Bod) calculated by PR Peneloux and SRK Peneloux EOS model for fluid JF_{13} at 377.55 K

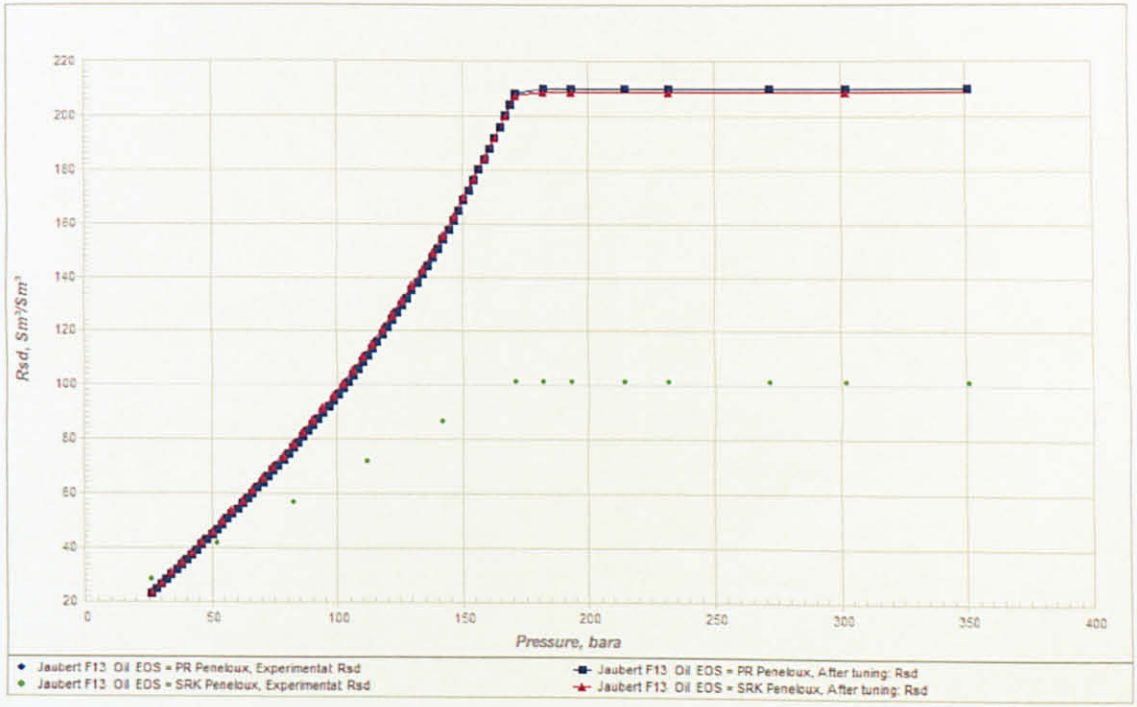

Figure 4.4: Comparison of solution GOR (Sm^3/Sm^3) calculated by PR Peneloux and SRK Peneloux EOS model for fluid JF_{13} at 377.55 K

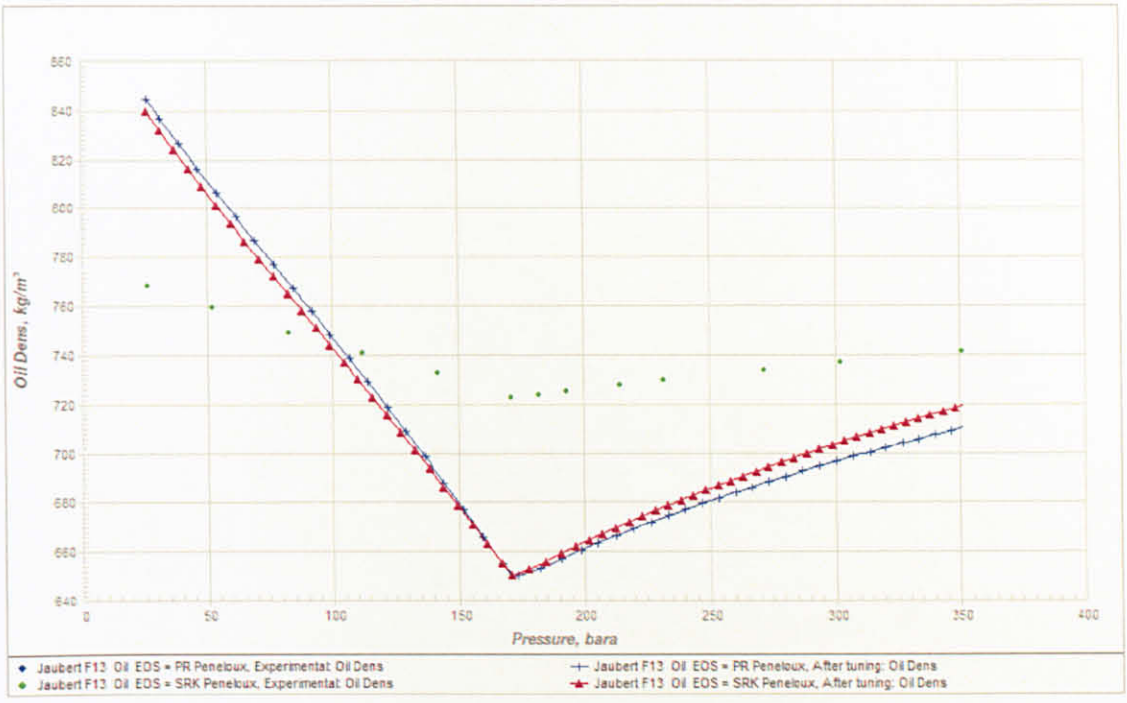

Figure 4.5: Comparison of DLE oil density (kg/m^3) calculated by PR Peneloux and SRK Peneloux EOS model for fluid JF_{13} at 377.55 K

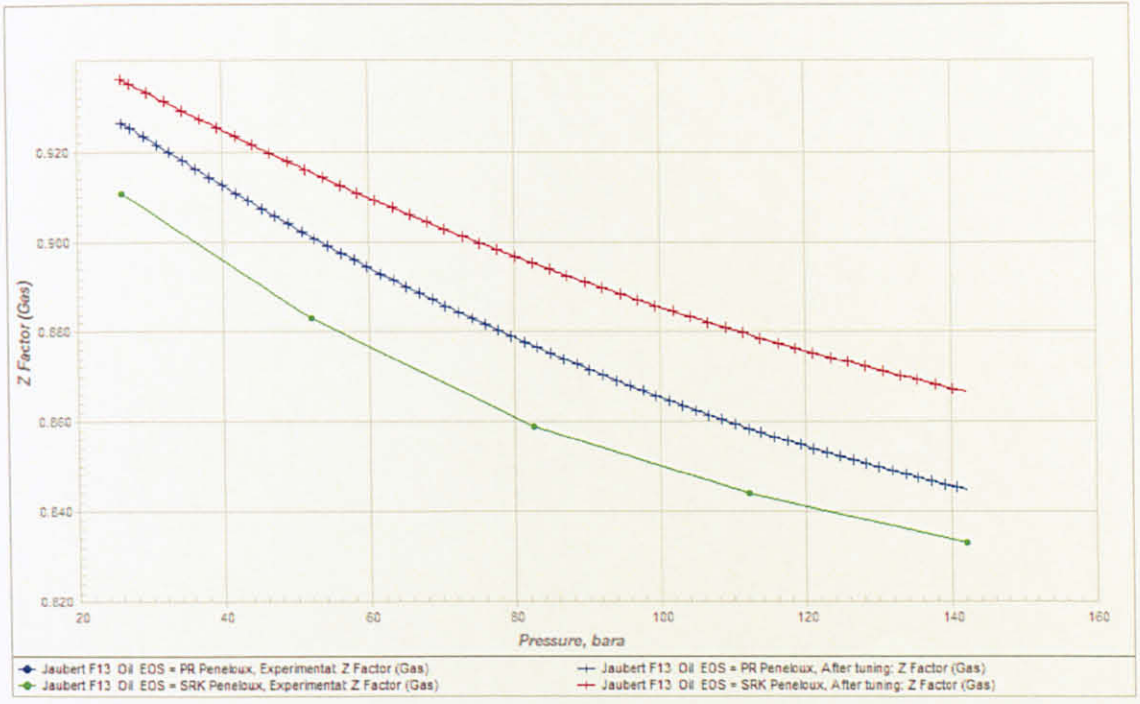

Figure 4.6: Comparison of gas Z-factor calculated by PR Peneloux and SRK Peneloux EOS model for fluid JF_{13} at 377.55 K

Figure 4.1 generally show both EOS predict the CME oil density and the relative volume with the same trend, which suggest that the tuning variables were adjusted with the same factors. For the oil formation volume factor (FVF) and solution gas-oil ratio (Rsd) in Figures 4.3 to 4.4, it is shown that both EOS over predict the data. The opposite trend is noticed for the DLE oil density, where both EOS under predict the data. The poor fit to the oil FVF, solution gas/oil ratio (Rsd) and DLE oil density is due to the inherent difficulty in matching all the data simultaneously. A better match of the Rsd and FVF data resulted in a poorer prediction of the densities and vice-versa. Regarding the gas Z-factor, it is observed that the PR Peneloux model estimation is quite close to the experimental value.

With regard to the MMP prediction, it is observed from the average absolute deviation (AAD) in Tables 4.3 to 4.4 that the PR Peneloux model predicts the MMP better than the SRK Peneloux model. However, if the individual percentage deviation of each model is taken into account, it could be said that the choice of which EOS is better rest on the condition of whether the model is tuned to the PVT data or not. It is shown that for the untuned case, the PR Peneloux model (percentage deviation -2.35 %) gives better prediction than the SRK Peneloux model although the latter gives better matching with other PVT data.

With regard to the tuned case, the SRK Peneloux model (percentage deviation -5.25 %) predicts the MMP better. Besides having lower deviation error in the matched saturation pressure, the SRK Peneloux model also gives better matches with other PVT properties. This is consistent with the observation of the untuned SRK Peneloux model.

By observing the data, several questions come to light: 1) Is it necessary to match the saturation pressure during the tuning before calculation the MMP? 2) How does the matching of other PVT properties influence the MMP prediction? By comparing the deviation error in saturation pressure and MMP calculation of the tuned case for both EOS model, it could be shown that accurate matching of the saturation pressure is indeed necessary for better

MMP prediction. Furthermore, it is also observed that as a result of accurate matching of saturation pressure, better matching of the other PVT properties is obtained, which influence the MMP prediction.

The small deviation error in the predicted MMP observed for the untuned PR Peneloux model compared to the SRK Peneloux model may compel one to further question whether tuning to PVT data is necessary at all. By comparing the other PVT properties in the PR Peneloux model for both the tuned and untuned case one may reach the conclusion that tuning to PVT data only increase the deviation error and subsequently reduce the accuracy of the predicted MMP.

Nevertheless, recent work by Egwuenu, Johns and Li (2005); Jessen and Stenby (2007); Stalkup and Yuan (2005) highlight this issue and suggested that including the MMP data together with the black oil PVT data may resolve the issue. However, this option is not explored further in this work due to limitation of the software used.

4.2 Selection of matching PVT data in the regression

The discussion in the previous section raised the question of how does matching the PVT parameters affect the MMP prediction. This question is explored further by highlighting another question: Which PVT parameters would most influence the MMP prediction?

The answer to this question is approached by selecting which PVT parameters to compare. For the benefit of discussion, the parameters are limited to the liquid phase densities (both from CME and DLE tests), the solution gas/oil ratio and the oil formation volume factor (FVF), both from DLE data. Following the characterization procedure outlined in the previous section, two EOS models are built with both using the PR Peneloux EOS. Initially all models are tuned to match the saturation pressure by using the Jessen and Stenby (2007) procedure. Then, the first model is tuned to match phase densities data by using the volume shift parameter. Similarly, the second

model is tuned to match the solution gas/oil ratio and the oil FVF by using the T_c and P_c. The tuning variables are applied to columns of pseudo-components. For the volume shift parameter, it is allowed to change by 50%, while for the rest, matching is obtained by adjusting the variables by 20%. Particularly for the oil FVF and the solution GOR case, the weight factors for these two items were set to five to highlight their relative importance in the regression process.

Table 4.3 compares each tuning objective to the saturation pressure, the oil density, the oil FVF and the solution GOR. Figures 4.7 to 4.10 show the trend for each tuning objective against the experimental data.

By observing the table, it can be said that matching the EOS model to liquid phase densities data by tuning the volume shift parameter achieves better prediction of MMP. The MMP deviation factor by tuning the EOS to match this data is only 0.33% as compared to the other tuning objectives. It is interesting to observe that all the models where tuned to obtain an acceptable match of saturation pressure (deviation error less than 1%).

However, when the MMP is calculated significant changes are observed in the results. For the model tuned to match solution GOR and oil FVF, it is shown that the MMP deviated by 15.22%. This observation implies that achieving acceptable match of saturation pressure does not ensure an accurate prediction of MMP if the model is not tuned to match the liquid phase densities.

Furthermore, it is noted in Figures 4.7 to 4.10 that there is a trade-off between achieving an acceptable match of liquid phase densities data and the solution GOR and the oil FVF. This is similar to the observation in the previous section. Adjusting the volume shift parameters to improve the match to the density data would adversely impact the prediction of solution GOR and oil FVF. Similarly, adjusting the T_c and P_c would also result in poor match to the density data. The best fit acceptable would be a balance between an excellent match to the density data and a fair match to the solution GOR and oil FVF.

Table 4.3: Experimental and calculated fluid sample properties for PR Peneloux EOS model (1) tuned to match GOR, (2) tuned to match CME oil density (3) tuned to match oil FVF

	Psat	% Dev	Density at Psat	% Dev	FVF at Psat	% Dev	Rs at Psat	% Dev	MMP	% Dev	% AAD
Experiment	171.00		722.54		1.25		101.60		271.00		
After tuning to match GOR (1)	172.55	0.91	606.03	-16.13	1.66	33.13	174.83	72.08	312.24	15.22	52.33
After tuning to match Oil Density (2)	172.24	0.73	658.78	-8.82	1.78	42.68	204.43	101.21	271.88	0.33	6.12
After tuning to match FVF(3)	172.55	0.91	606.03	-16.13	1.66	33.13	174.83	72.08	312.24	15.22	23.00

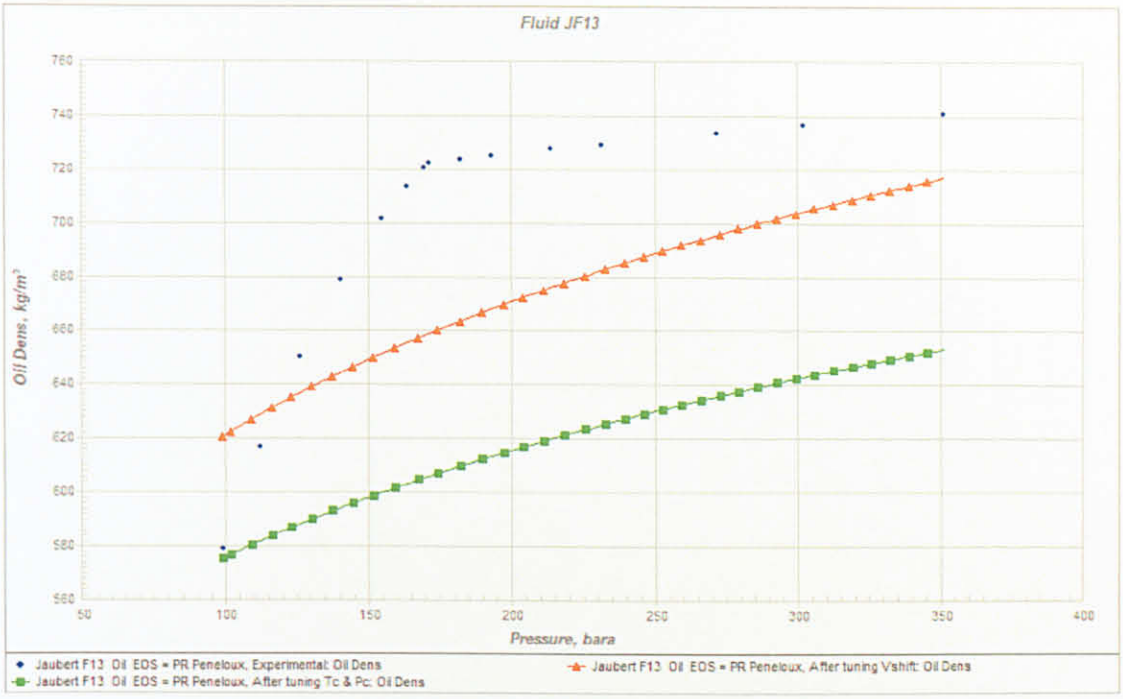

Figure 4.7: Comparison of calculated CME oil density by EOS model (1) tuned by volume shift parameter (Vshift) to match density (2) tuned by critical properties (T_c and P_c) to match solution GOR and oil FVF

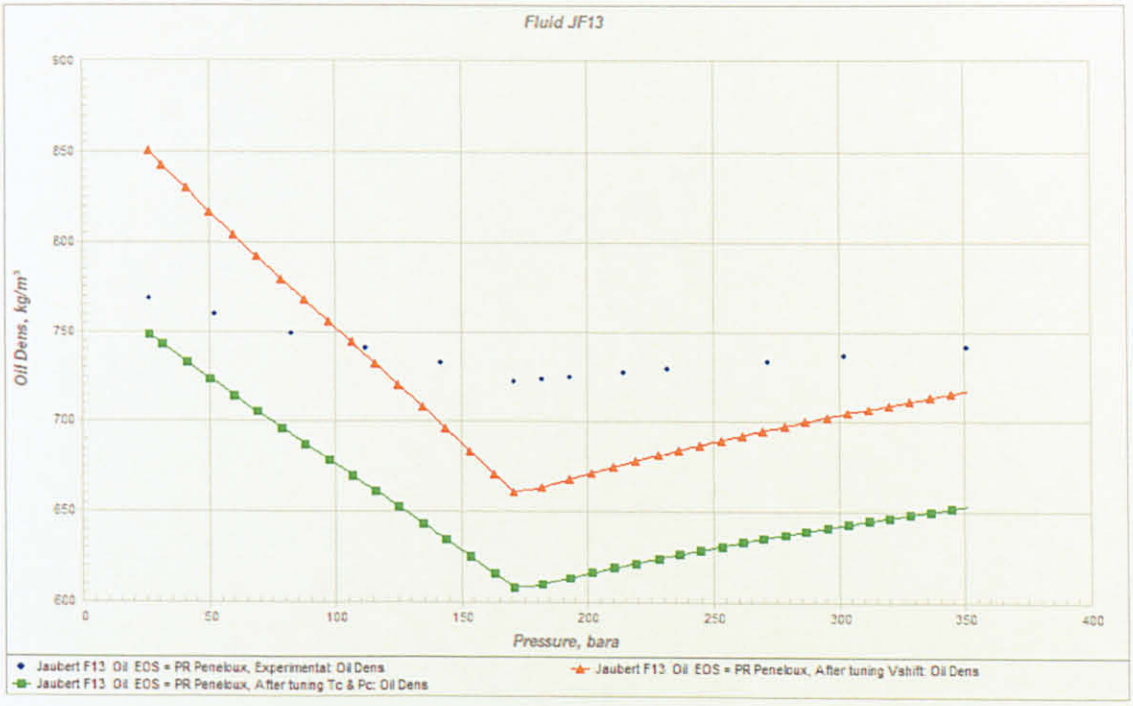

Figure 4.8: Comparison of calculated DLE oil density by EOS model (1) tuned by volume shift parameter (Vshift) to match density (2) tuned by critical properties (T_c and P_c) to match solution GOR and oil FVF

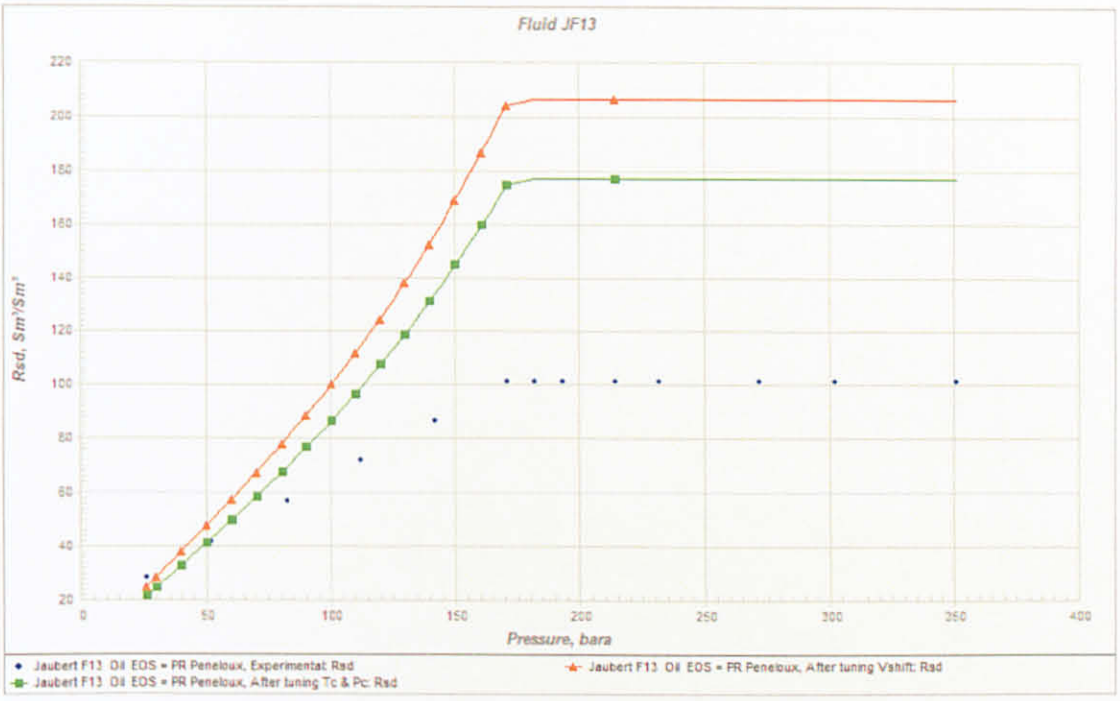

Figure 4.9: Comparison of calculated solution GOR by EOS model (1) tuned by volume shift parameter (Vshift) to match density (2) tuned by critical properties (T_c and P_c) to match solution GOR and oil FVF

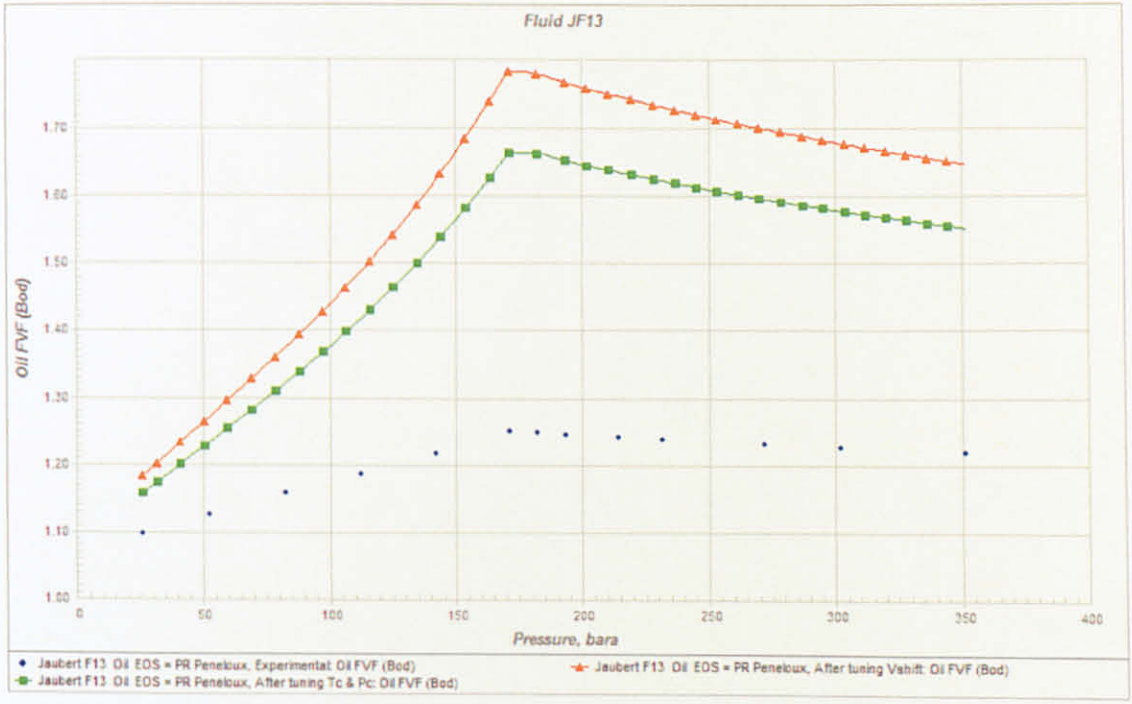

Figure 4.10: Comparison of calculated oil FVF by EOS model (1) tuned by volume shift parameter (Vshift) to match density (2) tuned by critical properties (T_c and P_c) to match solution GOR and oil FVF

4.3 Selection of regression strategy for MMP prediction

Apart from investigating the influence of the selection of EOS and matching PVT data in the prediction of MMP, the effect of tuning variables toward MMP calculation must also be understood. It is often said that tuning the EOS model to obtain an acceptable match with PVT data is more an art than science. This is due to the fact that there are many strategies proposed in the literature (Coats and Smart, 1986; Jessen and Stenby, 2007; Egwuenu, Johns and Li, 2005) to select which tuning variables to be used in the regression. However, some of the strategies are aimed toward getting an acceptable PVT match which is later used for generating PVT table in black oil simulation. Some others are developed for compositional simulation but only a few is aimed to match the PVT data for use in miscible flood simulation study.

In this section, two such strategies are investigated. The first is proposed by Coats and Smart (1986) and the second is used by Jessen and Stenby (2007). To obtain a match with the PVT data, Coats and Smart (1986) suggested tuning the following variables:

- Ω_A and Ω_B for the plus-fractions components.
- Ω_A and Ω_B of methane.
- Binary interaction coefficient, k_{ij}, between the methane and C_{7+} fractions.

Jessen and Stenby (2007) suggested the following:

- Molecular weight (MW) of the C_{7+} (adjustment up to maximum 10%)
- T_c and P_c of the plus-fractions column
- Acentric factor ω and volume shift parameter for subsequent tuning.

Two models are characterized with PR Peneloux EOS. The models are tuned to obtain an accurate match of saturation pressure (deviation error less than 1%). Next, the first model is tuned using Coats and Smart (1986) strategy. Ω_A and Ω_B of the plus-fractions and Ω_A and Ω_B of methane are adjusted by 20%. The binary interaction coefficient, k_{ij}, between the methane and C_{7+} fractions is changed by 10%.

For the second model using Jessen and Stenby (2007) strategy, molecular weight is changed by 10%, Tc, Pc and ω are adjusted by 20% and the volume shift is changed by 50%. These upper limits for EOS parameter adjustment help to make sure the PVT properties are not changed beyond unreasonable values.

Appendix E and Appendix F show the comparison of experimental and calculated data before and after tuning using both strategies. Appendix G and Appendix H show the MMP calculation for EOS models tuned by variables from both procedures.

Table 4.4 shows the comparison between both procedures and Figures 11 to 16 show the matching to PVT data obtained by both. From Table 4.4 it is shown that better prediction of MMP can be obtained by using the Jessen and Stenby (2007) procedure. Since both predict the saturation pressure accurately (deviation error less than 1%) it is noted than in terms of matching to PVT data, Coats and Smart (1986) procedure performs better. These are evident by looking at the properties shown in Figures 11 to 16.

According to Peng and Pope (2001) the better performance of Coats and Smart (1986) method in obtaining acceptable match to PVT data is due to the fact that tuning the parameters Ω_A and Ω_B of the PREOS is equivalent to tuning T_c and P_c. This condition is satisfied as long as the variables are bounded by some upper limit in order to guarantee a monotonic increase of T_c and a monotonic decrease of P_c as the carbon number increases.

From Table 4.5 comparison between both models and previous models with different EOS from Section 4.1 is shown. Here it is observed that the performance of Jessen and Stenby (2007) strategy to match all the PVT data

for MMP prediction is consistent (deviation error less than 10%). However, further observation reveals the SRK Peneloux EOS is better in predicting MMP (deviation error -5.25% compared to the rest). This is consistent with the findings in Section 4.1.

Furthermore this raises the question of why MMP calculation using PREOS has more deviation error than SRKEOS. As the miscible process is using pure CO_2, Jaubert, Avaullee and Pierre (2002) highlight the fact that PREOS has difficulty in predicting phase behaviour of mixtures containing a large amount of CO_2. This explains the reason of higher deviation error in prediction of other PVT data for PREOS as well as prediction of MMP. More over, this also highlight the fact that when the injection gas is 100 % CO_2, the EOS model should be characterized using SRK Peneloux EOS for accurate prediction of MMP.

4.4 Chapter Summary

In this chapter the analyses of the results are given. It is shown that SRK Peneloux is the better choice when predicting the MMP analytically when the miscible process is using pure CO_2. PR Peneloux is not effective for this situation as it has inherent weakness of predicting phase behaviour of pure CO_2. Apart from that it also shown that tuning the EOS model to match liquid phase density achieve better MMP prediction. Lastly, with regard to selection of tuning variables, it is shown that using the strategy proposed by Jessen and Stenby (2007) could help achieve more accurate prediction.

Table 4.4: Experimental and calculated fluid sample properties for PR Peneloux EOS model (1) tuned using Coats and Smart strategy (2) tuned using Jessen and Stenby strategy

	Psat	% Dev	Density at Psat	% Dev	FVF at Psat	% Dev	Rs at Psat	% Dev	MMP	% Dev
Experiment	171.00		722.54		1.25		101.60		271.00	
Coats & Smart	171.30	0.18	670.11	-7.26	1.69	34.93	197.06	93.96	349.96	29.13
Jessen & Stenby	171.47	0.28	657.56	-8.99	1.79	42.85	205.07	101.84	253.86	-6.33

Table 4.5: Comparison of experimental and calculated fluid sample properties with EOS models from section 4.1

Section	EOS		Psat	% Dev	Density at Psat	% Dev	FVF at Psat	% Dev	Rs at Psat	% Dev	MMP	% Dev
		Experiment	171.00		722.54		1.25		101.60		271.00	
4.3	PR Pen	Coats & Smart	171.30	0.18	670.11	-7.26	1.69	34.93	197.06	93.96	349.96	29.13
4.3	PR Pen	Jessen & Stenby	171.47	0.28	657.56	-8.99	1.79	42.85	205.07	101.84	253.86	-6.33
4.1	PR Pen	Jessen & Stenby	171.72	0.42	649.08	-10.2	1.842	47.3	208.4	105.1	247.96	-8.50
4.1	SRKPen	Jessen & Stenby	171.65	0.38	650.07	-10.0	1.846	47.6	207.7	104.4	256.76	-5.25

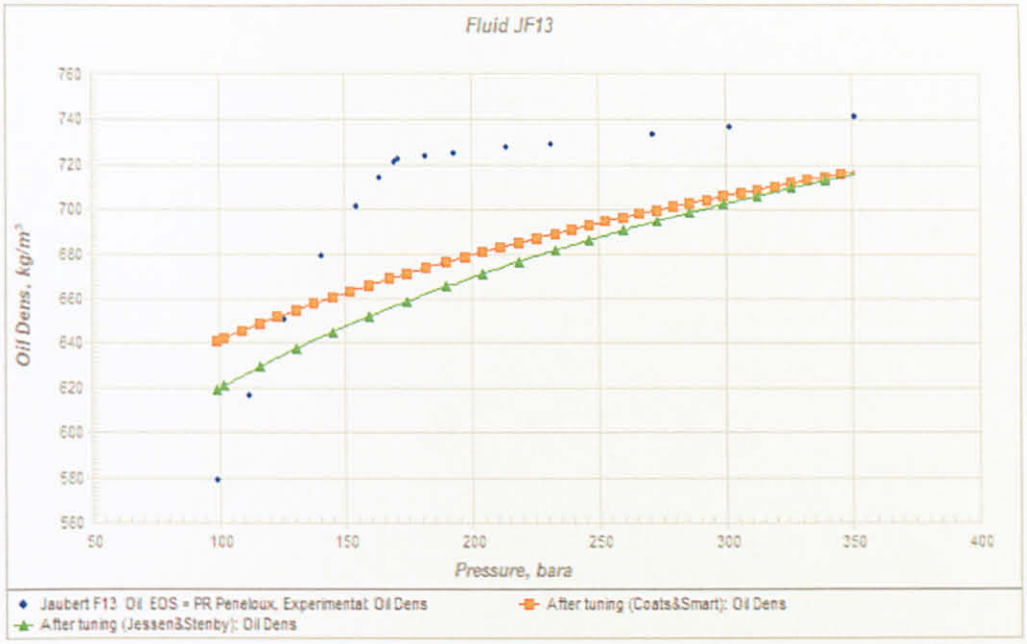

Figure 4.11: Comparison of calculated CME oil density by PR Peneloux EOS model (1) tuned using Coats and Smart strategy (2) tuned using Jessen and Stenby strategy

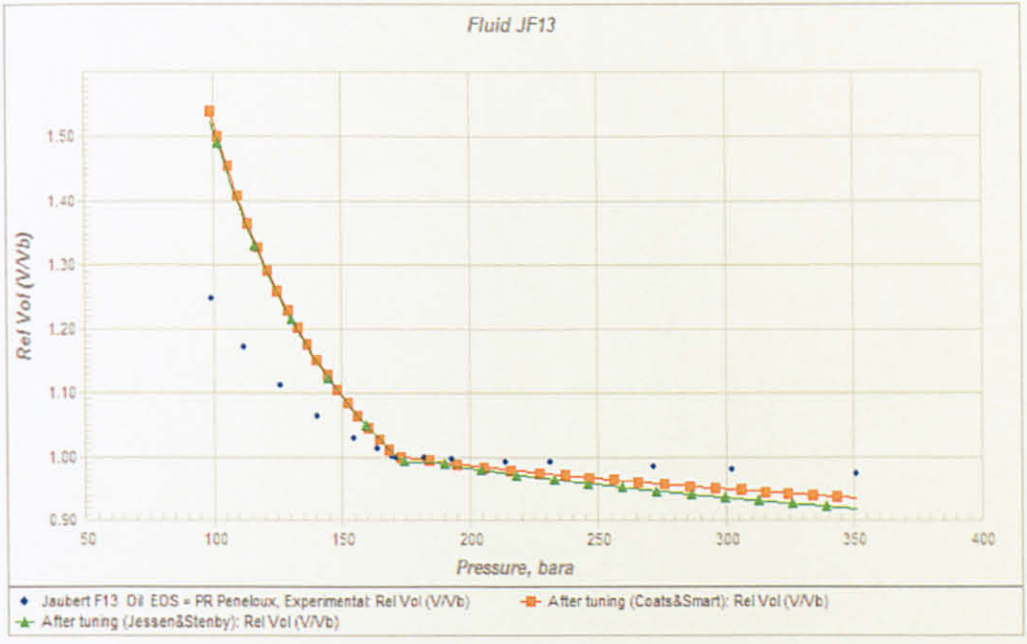

Figure 4.12: Comparison of calculated relative volume by PR Peneloux EOS model (1) tuned using Coats and Smart strategy (2) tuned using Jessen and Stenby strategy

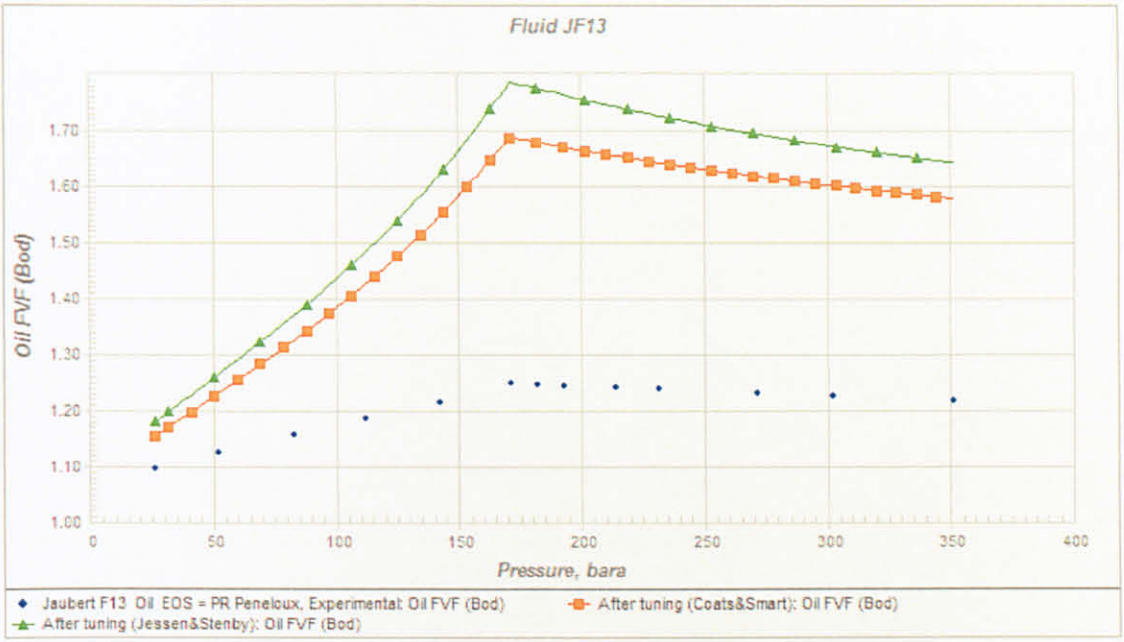

Figure 4.13: Comparison of calculated oil FVF by PR Peneloux EOS model (1) tuned using Coats and Smart strategy (2) tuned using Jessen and Stenby strategy

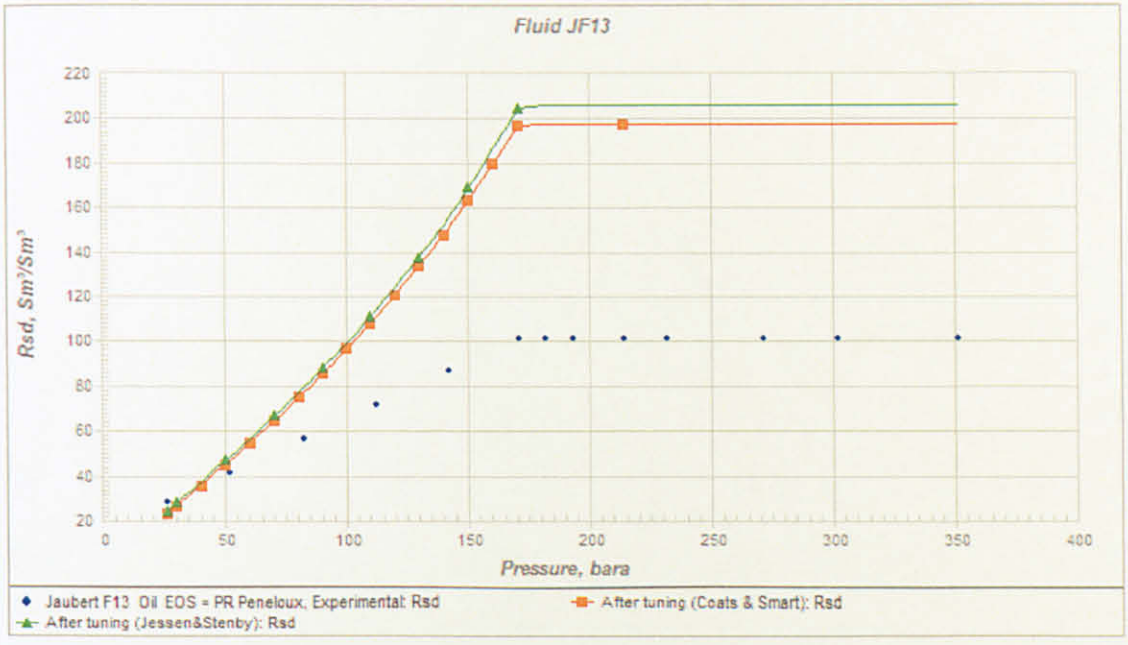

Figure 4.14: Comparison of calculated solution GOR by PR Peneloux EOS model (1) tuned using Coats and Smart strategy (2) tuned using Jessen and Stenby strategy

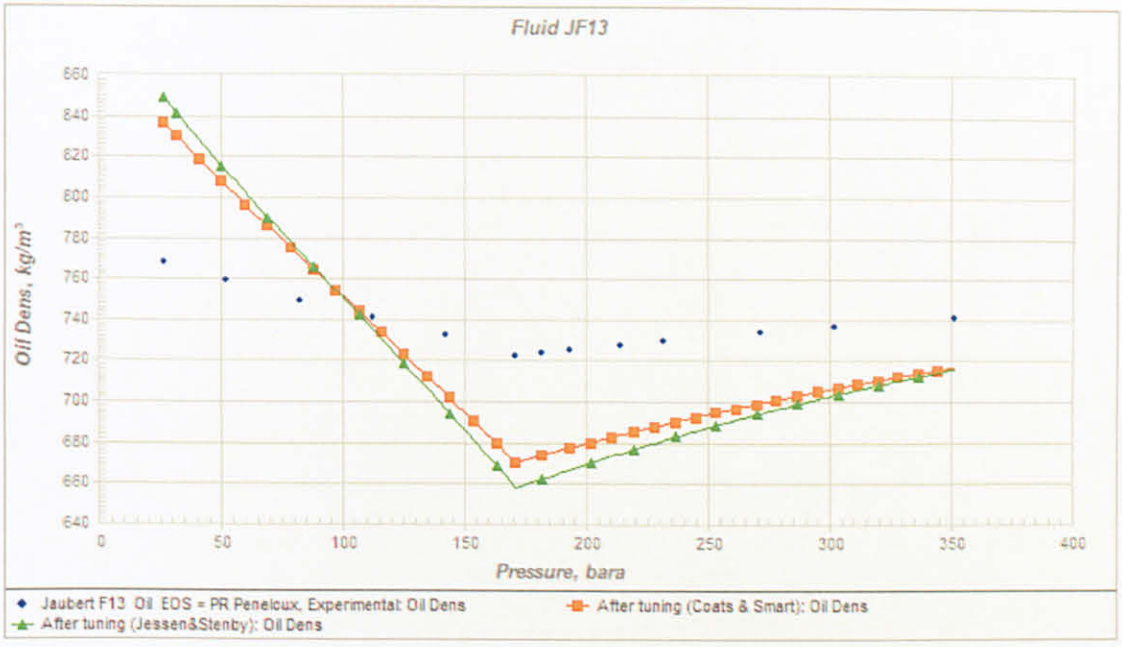

Figure 4.15: Comparison of calculated DLE oil density by PR Peneloux EOS model (1) tuned using Coats and Smart strategy (2) tuned using Jessen and Stenby strategy

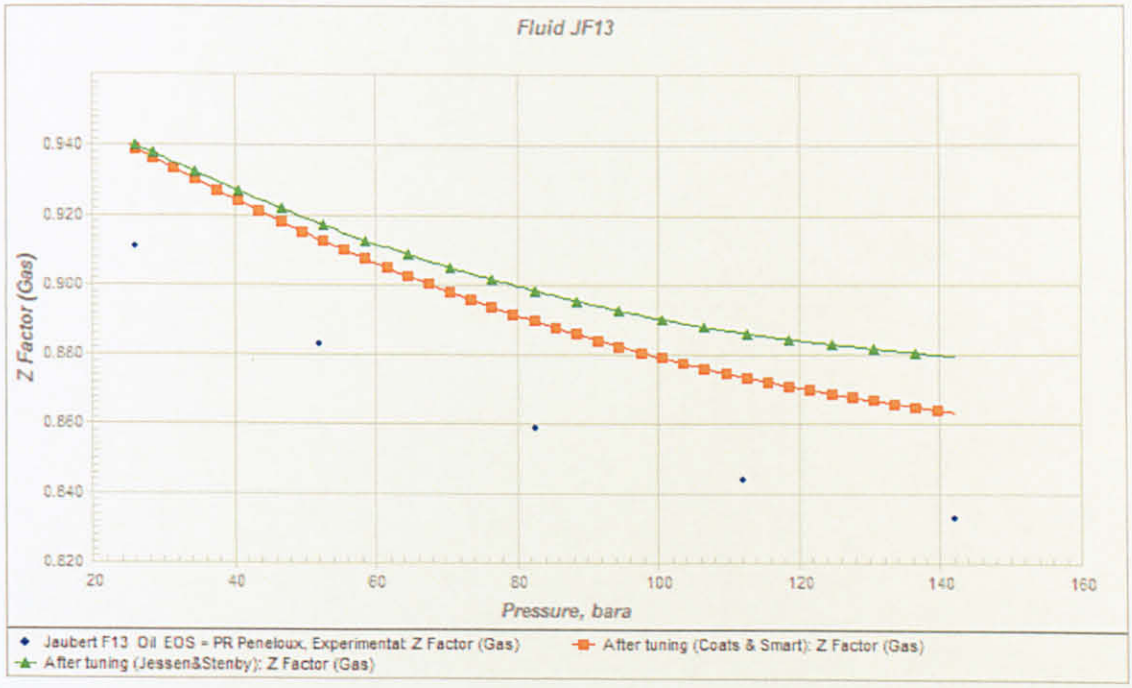

Figure 4.16: Comparison of calculated gas Z-factor by PR Peneloux EOS model (1) tuned using Coats and Smart strategy (2) tuned using Jessen and Stenby strategy

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research was approached by answering the following questions: 1) Which EOS is better in MMP prediction? 2) Which matching fluid properties bring more effect in MMP prediction? 3) Which EOS parameter used in tuning the equation influence MMP prediction? The main conclusions for each question are summarised below:

1. Selection of EOS

   - For pure CO_2 miscible displacement, SRK Peneloux is found to give better prediction of MMP (percentage deviation -5.25 %). The PR Peneloux gives poor prediction (percentage deviation -8.50 %) as it has limited capability to predict phase behaviour of mixtures with high amount of CO_2.

   - Accurate matching to saturation pressure is necessary to obtain accurate prediction of MMP as well as the other PVT properties. SRK Peneloux is shown to have this capability.

   - A more accurate MMP calculation can be obtained when the EOS model is tuned to match MMP data together with the black oil PVT data.

2. Selection of matching PVT data in the regression

   - Accurate matching of saturation pressure alone does not guarantee an accurate prediction of MMP if the density data is not matched properly.

   - Volume shift parameter can be adjusted to match density.

   - Solution GOR and oil FVF can be matched by adjusting T_c and P_c.

   - Achieving acceptable density match will result in poor fit to solution GOR and oil FVF. The approach is to maintain a balance between excellent density match and a fair match to solution GOR and oil FVF.

3. Selection of regression strategy for MMP prediction

   - The choice of tuning variables to use depends on the tuning strategies employed. It is shown that tuning strategy proposed by Jessen and Stenby (2007) can be used to adjust the EOS model to give better prediction of MMP.

   - Coats and Smart (1986) strategy is shown to match the PVT data better but the tuned EOS model gives poor MMP prediction.

5.2 Recommendations

The following suggestions for further research are made:

- The number of fluid samples can be extended in this study to give a better interpretation of data provided the compositional data and the PVT data are available. Apart from that, type of fluid studied can also include gas condensate, volatile oil and heavy oil.

- The conclusions drawn from this study are based on miscible displacement by pure CO_2 injection gas. This can be extended to

include case with contaminated and impure CO_2 as well as mixtures of other gases such as nitrogen and methane.

- The influence of the number of pseudo-components in the MMP prediction can also be studied. More pseudo-components mean longer simulation time as more flash calculations are done for each component. This entails doing a lumping study to determine the optimal number of pseudo-components to model the miscible process.

- Different EOS fluid characterization methods in the MMP prediction can also be investigated. This is to determine what characterization method is suitable for which EOS in order to predict the MMP.

- The MMP in this study is calculated using analytical technique. A comparison study can be made to other methods such as 1-D slim-tube simulation and mixed-cell method to determine the accuracy of MMP predicted in each case.

- Study to analyse the influence of numerical dispersion in the MMP prediction using analytical technique can be made. This can be done by using the compositional simulation to model the slim – tube displacement using different grid resolution.

Appendix A: PVTSIM EOS Regression Module

The regression menus showing the different options available for tuning an EOS characterization are given below:

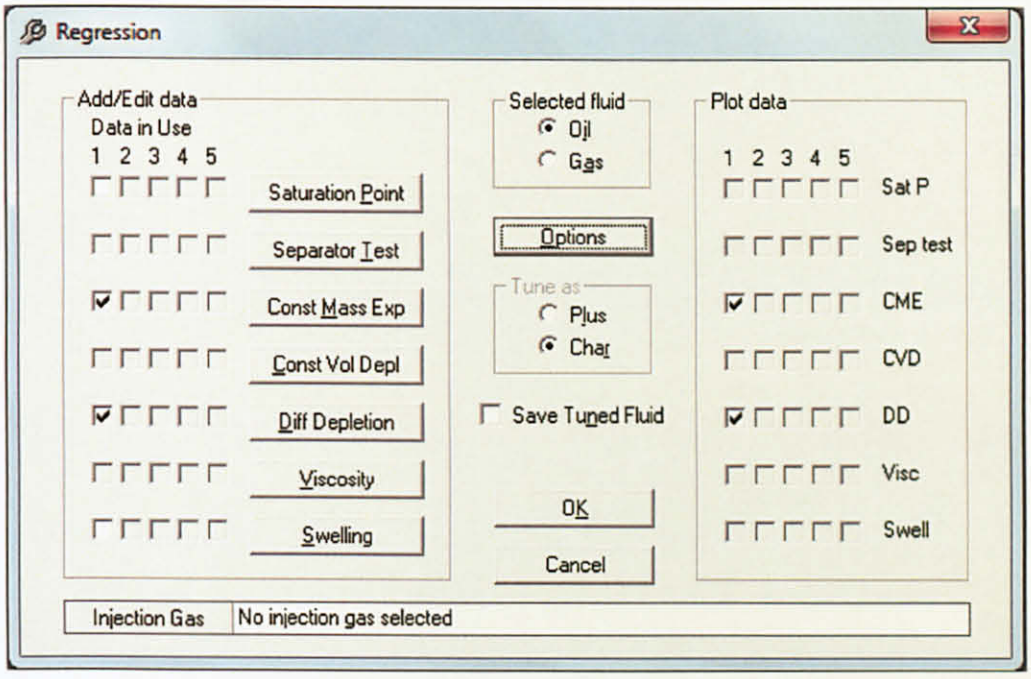

Illustration 1: PVT data selection menu for PVTSIM regression tool.

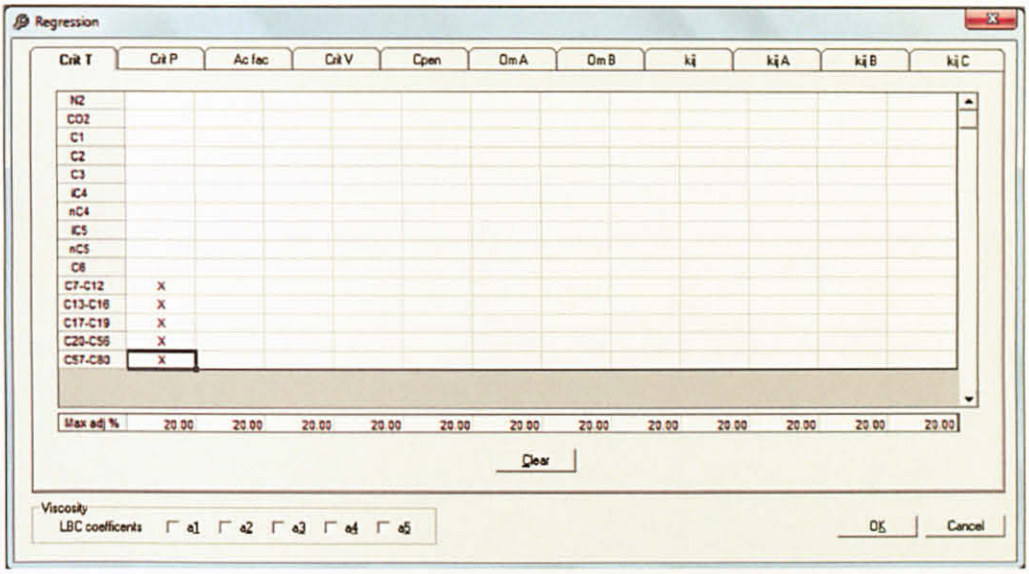

Illustration 2: Menu for EOS variables for regression.

11. Create another fluid file for the injection gas by following steps four to ten.

12. Make sure the same EOS is selected for the whole procedure.

B2: Characterization to same pseudo-components

Before doing MMP simulation, the oil and injection gas need to be characterized to the same pseudo-components. This is to ensure that all injection gas components are found in the reservoir fluid. If a gas component is encountered that is not found in the reservoir fluid, a message will appear with information about the first component in the injection gas not being matched in the reservoir fluid.

1. Go to "Simulations Explorer – Fluid – Same Pseudos" and press to open the "Characterization to the Same Pseudo-Components" window as shown in Illustration 2.

2. Press "Select Fluid" button to select the oil and the injection gas.

3. Press "OK" to complete the characterization.

B3: MMP simulation

1. In the "Simulations Explorer" press "Simulations" and select "MMP" in the "Reservoir" section. An "MMP" window will appear as shown in Illustration 3.

2. Select the injection gas. Since the oil and injection gas has been characterized to the same pseudo-components, the gas entry will have the tag "Same Ps".

3. Enter the required temperature and press "OK".

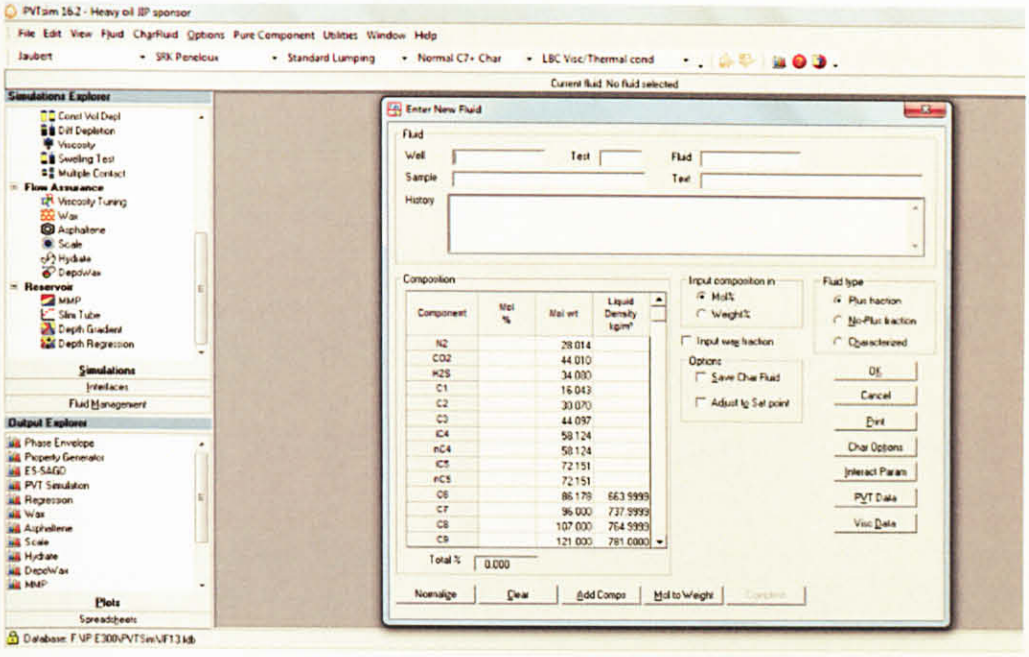

Illustration 3: PVTSim input menu for fluid composition and properties

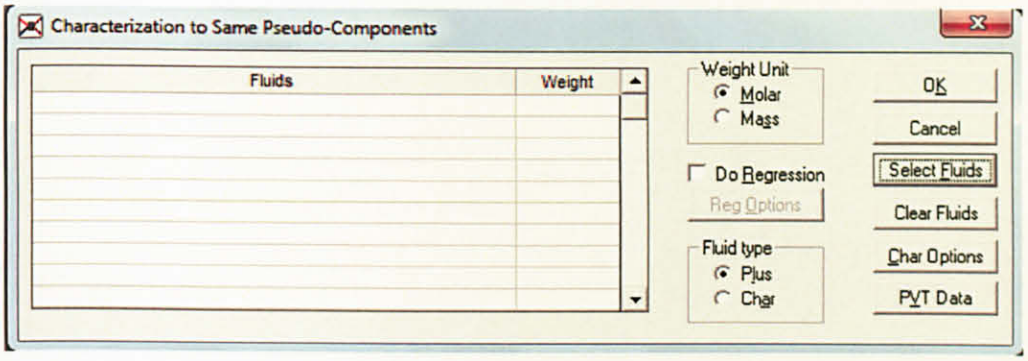

Illustration 4: PVTsim input menu for characterization to same pseudo-components

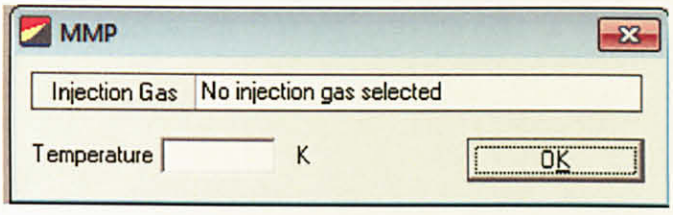

Illustration 5: MMP simulation menu for PVTsim

Appendix C: Component properties for 15-component PR Peneloux EOS model

Component	Mol %	Mol Wt	Liquid Density (kg/m3)	Crit T (K)	Crit P (bara)	Acentric Factor	Normal Tb (K)	Crit V (m3/mol)	Cpen (m3/mol)	Omega A	Omega B
N2	1.572	28.014		126.2	33.94	0.04	77.4	8.98E-05	-4.23E-06	0.45724	0.0778
CO2	1.126	44.01		304.2	73.76	0.225	194.65	9.40E-05	-1.64E-06	0.45724	0.0778
C1	47.14	16.043		190.6	46	0.008	111.6	9.90E-05	-5.20E-06	0.45724	7.78E-02
C2	6.876	30.07		305.4	48.84	0.098	184.6	1.48E-04	-5.79E-06	0.45724	0.0778
C3	5.269	44.097		369.8	42.46	0.152	231.1	2.03E-04	-6.35E-06	0.45724	0.0778
iC4	1.386	58.124		408.1	36.48	0.176	261.4	2.63E-04	-7.18E-06	0.45724	0.0778
nC4	3.644	58.124		425.2	38	0.193	272.7	2.55E-04	-6.49E-06	0.45724	0.0778
iC5	1.708	72.151		460.4	33.84	0.227	301	3.06E-04	-6.20E-06	0.45724	0.0778

Appendix C (cont'): Component properties for 15-component PR Peneloux EOS model

Component	Mol %	Mol Wt	Liquid Density (kg/m3)	Crit T (K)	Crit P (bara)	Acentric Factor	Normal Tb (K)	Crit V (m3/mol)	Cpen (m3/mol)	Omega A	Omega B
nC5	2.354	72.151		469.6	33.74	0.251	309.2	3.04E-04	-5.12E-06	0.45724	0.0778
C6	1.61	86	682.2	507.4	29.69	0.296	341.9	3.70E-04	1.39E-06	0.45724	0.0778
C7-C12	10.264	137.252	766.306	608	22.49	0.481	448.544	6.29E-04	1.55E-05	0.45724	7.78E-02
C13-C16	8.828	197.67	808.319	687.708	17.94	0.6665	530.12	8.52E-04	2.28E-05	0.45724	7.78E-02
C17-C19	4.244	260.284	828.445	755.78	15.54	0.8404	584.888	1.11E-03	1.89E-05	0.45724	7.78E-02
C20-C56	2.532	521.333	881.151	1023.02	12.27	1.1747	789.565	2.56E-03	-3.64E-05	0.45724	7.78E-02
C57-C80	1.447	952.221	918.631	1328.8	10.98	0.5044	951.801	4.57E-03	-2.29E-04	0.45724	7.78E-02

Appendix D: Component properties for 15-component SRK Peneloux EOS model

Component	Mol %	Mol Wt	Liquid Density (kg/m3)	Crit T (K)	Crit P (bara)	Acentric Factor	Normal Tb (K)	Crit V (m3/mol)	Cpen (m3/mol)	Omega A	Omega B
N2	1.572	28.014		126.2	33.94	0.04	77.4	8.98E-05	9.20E-07	0.42748	0.08664
CO2	1.126	44.01		304.2	73.76	0.225	194.65	9.40E-05	3.03E-06	0.42748	8.66E-02
C1	47.14	16.043		190.6	46	0.008	111.6	9.90E-05	6.30E-07	0.42748	0.08664
C2	6.876	30.07		305.4	48.84	0.098	184.6	1.48E-04	2.63E-06	0.42748	0.08664
C3	5.269	44.097		369.8	42.46	0.152	231.1	2.03E-04	5.06E-06	0.42748	0.08664
iC4	1.386	58.124		408.1	36.48	0.176	261.4	2.63E-04	7.29E-06	0.42748	0.08664
nC4	3.644	58.124		425.2	38	0.193	272.7	2.55E-04	7.86E-06	0.42748	0.08664
iC5	1.708	72.151		460.4	33.84	0.227	301	3.06E-04	1.09E-05	0.42748	0.08664

Appendix D (cont'): Component properties for 15-component SRK Peneloux EOS model

Component	Mol %	Mol Wt	Liquid Density (kg/m3)	Crit T (K)	Crit P (bara)	Acentric Factor	Normal Tb (K)	Crit V (m3/mol)	Cpen (m3/mol)	Omega A	Omega B
nC5	2.354	72.151		469.6	33.74	0.251	309.2	3.04E-04	1.22E-05	0.42748	0.08664
C6	1.61	86	682.2	507.4	29.69	0.296	341.9	3.70E-04	1.80E-05	0.42748	0.08664
C7-C12	10.264	137.252	766.306	596.628	22.34	0.5921	448.544	6.29E-04	3.56E-05	0.42748	8.66E-02
C13-C16	8.828	197.67	808.319	664.584	17.38	0.7509	530.12	8.52E-04	5.42E-05	0.42748	8.66E-02
C17-C19	4.244	260.284	828.445	719.953	14.79	0.8989	584.888	1.11E-03	5.97E-05	0.42748	8.66E-02
C20-C56	2.532	521.333	881.151	927.457	11.83	1.2813	789.565	2.56E-03	-7.82E-06	0.42748	8.66E-02
C57-C80	1.447	952.221	918.631	1156.81	10.94	1.0274	951.801	4.57E-03	-2.54E-04	0.42748	8.66E-02

Appendix E: Comparison of experimental and calculated data before and after tuning with Coats and Smart (1986) tuning strategy

Constant Mass Expansion at 377.55 K
CME

Saturation Pressure		Weight=	50.00		
bara					
Temp	**Exp**	**Before**	**%Dev**	**After**	**%Dev**
K	**value**	**tuning**	**before**	**tuning**	**after**
377.55	171.00	172.24	0.7	171.30	0.2

Rel Vol		Weight=	1.00		
V/Vb					
Pressure	**Exp**	**Before**	**%Dev**	**After**	**%Dev**
bara	**value**	**tuning**	**before**	**tuning**	**after**
351.00	0.9740	0.9241	-5.1	0.9348	-4.0
302.00	0.9810	0.9398	-4.2	0.9486	-3.3
271.50	0.9850	0.9511	-3.4	0.9584	-2.7
231.50	0.9910	0.9681	-2.3	0.9730	-1.8
214.00	0.9930	0.9766	-1.7	0.9801	-1.3
193.00	0.9960	0.9877	-0.8	0.9894	-0.7
182.00	0.9980	0.9941	-0.4	0.9946	-0.3
171.00	1.0000	1.0043	0.4	1.0012	0.1
169.50	1.0020	1.0097	0.8	1.0070	0.5
163.70	1.0120	1.0315	1.9	1.0307	1.8
154.70	1.0300	1.0695	3.8	1.0720	4.1
140.50	1.0640	1.1417	7.3	1.1506	8.1
126.00	1.1110	1.2359	11.2	1.2534	12.8
112.00	1.1710	1.3544	15.7	1.3827	18.1
99.00	1.2470	1.4994	20.2	1.5408	23.6

Density		Weight=	10.00		
kg/m³					
Pressure	**Exp**	**Before**	**%Dev**	**After**	**%Dev**
bara	**value**	**tuning**	**before**	**tuning**	**after**
351.00	741.2900	672.5499	-9.3	716.9232	-3.3
302.00	736.9200	661.3358	-10.3	706.5039	-4.1
271.50	733.6760	653.5067	-10.9	699.2997	-4.7
231.50	729.3950	642.0041	-12.0	688.8258	-5.6
214.00	727.8020	636.4428	-12.6	683.8117	-6.0
193.00	725.1630	629.2615	-13.2	677.3875	-6.6
182.00	724.1130	625.2499	-13.7	673.8247	-6.9
171.00	722.5430	621.0458	-14.0	670.1115	-7.3

169.50	720.9810	620.4567	-13.9	669.5928	-7.1
163.70	713.7760	618.1406	-13.4	667.5582	-6.5
154.70	701.7540	614.4215	-12.4	664.3052	-5.3
140.50	678.8870	608.2150	-10.4	658.9166	-2.9
126.00	650.6180	601.3929	-7.6	653.0543	0.4
112.00	616.9030	594.2659	-3.7	647.0016	4.9
99.00	579.3740	587.0903	1.3	640.9863	10.6

Differential Depletion at 377.55 K
DVT

Saturation Pressure bara		Weight=	50.00		
Temp K	**Exp value**	**Before tuning**	**%Dev before**	**After tuning**	**%Dev after**
377.55	171.00	172.24	0.7	171.30	0.2

Oil FVF Bod		Weight=	1.00		
Pressure bara	**Exp value**	**Before tuning**	**%Dev before**	**After tuning**	**%Dev after**
351.00	1.219	1.586	30.1	1.579	29.5
302.00	1.226	1.613	31.6	1.602	30.6
271.50	1.231	1.633	32.6	1.619	31.5
231.50	1.238	1.662	34.2	1.643	32.7
214.00	1.242	1.676	35.0	1.655	33.3
193.00	1.246	1.696	36.1	1.671	34.1
182.00	1.249	1.706	36.7	1.680	34.5
171.00	1.250	1.709	36.7	1.687	34.9
142.00	1.217	1.563	28.4	1.546	27.0
112.00	1.187	1.440	21.2	1.426	20.0
82.50	1.159	1.337	15.4	1.325	14.3
52.00	1.126	1.244	10.4	1.232	9.4
26.00	1.097	1.166	6.2	1.154	5.2
1.00	1.000	1.000	0.0	1.000	0.0

Rsd Sm^3/Sm^3		Weight=	1.00		
Pressure bara	**Exp value**	**Before tuning**	**%Dev before**	**After tuning**	**%Dev after**
351.00	101.6	186.7	83.8	197.6	94.5
302.00	101.6	186.7	83.8	197.6	94.5
271.50	101.6	186.7	83.8	197.6	94.5
231.50	101.6	186.7	83.8	197.6	94.5
214.00	101.6	186.7	83.8	197.6	94.5
193.00	101.6	186.7	83.8	197.6	94.5
182.00	101.6	186.7	83.8	197.6	94.5

171.00	101.6	184.6	81.7	197.1	94.0
142.00	86.8	140.4	61.8	150.5	73.4
112.00	72.0	103.2	43.3	110.6	53.6
82.50	57.1	72.4	26.7	77.3	35.3
52.00	42.0	44.6	6.1	47.2	12.3
26.00	28.4	22.4	-21.0	23.2	-18.1
1.00	0.0				

Oil Dens Weight= 10.00
kg/m³

Pressure bara	**Exp value**	**Before tuning**	**%Dev before**	**After tuning**	**%Dev after**
351.00	741.6000	672.5499	-9.3	716.9232	-3.3
302.00	736.9000	661.3358	-10.3	706.5039	-4.1
271.50	733.8000	653.5067	-10.9	699.2997	-4.7
231.50	729.5000	642.0041	-12.0	688.8258	-5.6
214.00	727.6000	636.4428	-12.5	683.8117	-6.0
193.00	725.1000	629.2615	-13.2	677.3875	-6.6
182.00	723.9000	625.2499	-13.6	673.8247	-6.9
171.00	722.6000	622.9296	-13.8	670.5652	-7.2
142.00	732.8000	655.0244	-10.6	704.0995	-3.9
112.00	741.1000	687.1158	-7.3	737.9954	-0.4
82.50	749.3000	718.0885	-4.2	770.9680	2.9
52.00	759.5000	750.3826	-1.2	805.5089	6.1
26.00	768.2000	779.9085	1.5	837.1167	9.0
1.00	790.2000	877.2794	11.0	933.7908	18.2

Z Factor Weight= 1.00
Gas

Pressure bara	**Exp value**	**Before tuning**	**%Dev before**	**After tuning**	**%Dev after**
142.00	0.833	0.880	5.7	0.863	3.6
112.00	0.844	0.887	5.0	0.874	3.5
82.50	0.859	0.899	4.6	0.890	3.6
52.00	0.883	0.918	3.9	0.913	3.4
26.00	0.911	0.940	3.2	0.939	3.1
1.00	1.000	0.990	-1.0	0.990	-1.0

Last Stage is a Standard Stage

General Regression Results

Object function before tuning	4.379E-01

Object function after tuning	3.036E-01

Corr fac 1: Omega A PR. Max adjustment: 10.00%.

	Before tuning	After tuning	%Adjustment
C7-C12	0.45724	0.47936	4.839
C13-C15	0.45724	0.47936	4.839
C16-C19	0.45724	0.47936	4.839
C20-C56	0.45724	0.47936	4.839
C57-C80	0.45724	0.47936	4.839

Corr fac 2: Omega A PR. Max adjustment: 10.00%.

	Before tuning	After tuning	%Adjustment
C1	0.45724	0.45807	0.181

Corr fac 3: Omega B PR. Max adjustment: 10.00%.

	Before tuning	After tuning	%Adjustment
C7-C12	0.07780	0.07441	-4.357
C13-C15	0.07780	0.07441	-4.357
C16-C19	0.07780	0.07441	-4.357
C20-C56	0.07780	0.07441	-4.357
C57-C80	0.07780	0.07441	-4.357

Corr fac 4: Omega B PR. Max adjustment: 10.00%.

	Before tuning	After tuning	%Adjustment
C1	0.07780	0.07002	-10.000

Corr fac 5: PR kij. Max adjustment: 0.1000.

	Before tuning
	C1
C7-C12	0.0000
C13-C15	0.0000
C16-C19	0.0000
C20-C56	0.0000
C57-C80	0.0000

	C1	After tuning
C7-C12	-0.0257	
C13-C15	-0.0257	
C16-C19	-0.0257	
C20-C56	-0.0257	
C57-C80	-0.0257	

Sensitivity matrix:

Corr fac	d(Obj)/d(Corr fac)
1	7.33E-01
2	-1.14E+00
3	8.87E-01
4	1.58E+00
5	2.78E+00

Appendix F: Comparison of experimental and calculated data before and after tuning with Jessen and Stenby (2007) tuning strategy

Constant Mass Expansion at 377.55 K
CME

Saturation Pressure bara		Weight=	50.00		
Temp K	Exp value	Before tuning	%Dev before	After tuning	%Dev after
377.55	171.00	172.24	0.7	171.47	0.3

Rel Vol V/Vb		Weight=	1.00		
Pressure bara	Exp value	Before tuning	%Dev before	After tuning	%Dev after
351.00	0.9740	0.9241	-5.1	0.9185	-5.7
302.00	0.9810	0.9398	-4.2	0.9352	-4.7
271.50	0.9850	0.9511	-3.4	0.9472	-3.8
231.50	0.9910	0.9681	-2.3	0.9654	-2.6
214.00	0.9930	0.9766	-1.7	0.9744	-1.9
193.00	0.9960	0.9877	-0.8	0.9863	-1.0
182.00	0.9980	0.9941	-0.4	0.9931	-0.5
171.00	1.0000	1.0043	0.4	1.0018	0.2
169.50	1.0020	1.0097	0.8	1.0075	0.5
163.70	1.0120	1.0315	1.9	1.0307	1.8
154.70	1.0300	1.0695	3.8	1.0710	4.0
140.50	1.0640	1.1417	7.3	1.1477	7.9
126.00	1.1110	1.2359	11.2	1.2476	12.3
112.00	1.1710	1.3544	15.7	1.3731	17.3
99.00	1.2470	1.4994	20.2	1.5267	22.4

Density kg/m³		Weight=	10.00		
Pressure bara	Exp value	Before tuning	%Dev before	After tuning	%Dev after
351.00	741.2900	672.5499	-9.3	716.1202	-3.4
302.00	736.9200	661.3358	-10.3	703.3487	-4.6
271.50	733.6760	653.5067	-10.9	694.4405	-5.3
231.50	729.3950	642.0041	-12.0	681.3633	-6.6
214.00	727.8020	636.4428	-12.6	675.0448	-7.2
193.00	725.1630	629.2615	-13.2	666.8892	-8.0
182.00	724.1130	625.2499	-13.7	662.3348	-8.5
171.00	722.5430	621.0458	-14.0	657.5627	-9.0
169.50	720.9810	620.4567	-13.9	656.8940	-8.9

163.70	713.7760	618.1406	-13.4	654.2656	-8.3
154.70	701.7540	614.4215	-12.4	650.0453	-7.4
140.50	678.8870	608.2150	-10.4	643.0033	-5.3
126.00	650.6180	601.3929	-7.6	635.2639	-2.4
112.00	616.9030	594.2659	-3.7	627.1785	1.7
99.00	579.3740	587.0903	1.3	619.0372	6.8

Differential Depletion at 377.55 K
DVT

Saturation Pressure Weight= 50.00
bara

Temp K	Exp value	Before tuning	%Dev before	After tuning	%Dev after
377.55	171.00	172.24	0.7	171.47	0.3

Oil FVF Weight= 1.00
Bod

Pressure bara	Exp value	Before tuning	%Dev before	After tuning	%Dev after
351.00	1.219	1.586	30.1	1.643	34.8
302.00	1.226	1.613	31.6	1.673	36.5
271.50	1.231	1.633	32.6	1.695	37.7
231.50	1.238	1.662	34.2	1.727	39.5
214.00	1.242	1.676	35.0	1.744	40.4
193.00	1.246	1.696	36.1	1.765	41.7
182.00	1.249	1.706	36.7	1.777	42.3
171.00	1.250	1.709	36.7	1.786	42.8
142.00	1.217	1.563	28.4	1.622	33.3
112.00	1.187	1.440	21.2	1.484	25.0
82.50	1.159	1.337	15.4	1.371	18.3
52.00	1.126	1.244	10.4	1.267	12.5
26.00	1.097	1.166	6.2	1.181	7.6
1.00	1.000	1.000	0.0	1.000	0.0

Rsd Weight= 1.00
Sm^3/Sm^3

Pressure bara	Exp value	Before tuning	%Dev before	After tuning	%Dev after
351.00	101.6	186.7	83.8	206.0	102.7
302.00	101.6	186.7	83.8	206.0	102.7
271.50	101.6	186.7	83.8	206.0	102.7
231.50	101.6	186.7	83.8	206.0	102.7
214.00	101.6	186.7	83.8	206.0	102.7
193.00	101.6	186.7	83.8	206.0	102.7
182.00	101.6	186.7	83.8	206.0	102.7
171.00	101.6	184.6	81.7	205.1	101.8

142.00	86.8	140.4	61.8	155.6	79.3
112.00	72.0	103.2	43.3	114.1	58.5
82.50	57.1	72.4	26.7	80.0	40.0
52.00	42.0	44.6	6.1	49.2	17.2
26.00	28.4	22.4	-21.0	24.8	-12.8
1.00	0.0				

Oil Dens Weight= 10.00
kg/m³

Pressure bara	Exp value	Before tuning	%Dev before	After tuning	%Dev after
351.00	741.6000	672.5499	-9.3	716.1202	-3.4
302.00	736.9000	661.3358	-10.3	703.3487	-4.6
271.50	733.8000	653.5067	-10.9	694.4405	-5.4
231.50	729.5000	642.0041	-12.0	681.3633	-6.6
214.00	727.6000	636.4428	-12.5	675.0448	-7.2
193.00	725.1000	629.2615	-13.2	666.8892	-8.0
182.00	723.9000	625.2499	-13.6	662.3348	-8.5
171.00	722.6000	622.9296	-13.8	658.4038	-8.9
142.00	732.8000	655.0244	-10.6	696.7665	-4.9
112.00	741.1000	687.1158	-7.3	735.4218	-0.8
82.50	749.3000	718.0885	-4.2	773.0561	3.2
52.00	759.5000	750.3826	-1.2	812.7151	7.0
26.00	768.2000	779.9085	1.5	849.4943	10.6
1.00	790.2000	877.2794	11.0	967.8261	22.5

Z Factor Weight= 1.00
Gas

Pressure bara	Exp value	Before tuning	%Dev before	After tuning	%Dev after
142.00	0.833	0.880	5.7	0.880	5.6
112.00	0.844	0.887	5.0	0.886	5.0
82.50	0.859	0.899	4.6	0.898	4.6
52.00	0.883	0.918	3.9	0.918	3.9
26.00	0.911	0.940	3.2	0.940	3.2
1.00	1.000	0.990	-1.0	0.990	-1.0

Last Stage is a Standard Stage

General Regression Results

Object function before tuning	4.379E-01
Object function after tuning	3.628E-

Corr fac 1: Crit T (K). Max adjustment: 20.00%.

	Before tuning	After tuning	%Adjustment of Crit T in K
C7-C12	597.106	615.730	3.119
C13-C15	652.622	672.978	3.119
C16-C19	701.422	723.299	3.119
C20-C56	895.784	923.724	3.119
C57-C80	1102.084	1136.458	3.119

Corr fac 2: Crit P (bara). Max adjustment: 20.00%.

	Before tuning	After tuning	%Adjustment
C7-C12	17.99	18.98	5.521
C13-C15	14.73	15.55	5.521
C16-C19	12.67	13.37	5.521
C20-C56	9.79	10.33	5.521
C57-C80	8.77	9.26	5.521

Corr fac 3: Acentric factor. Max adjustment: 20.00%.

	Before tuning	After tuning	%Adjustment
C7-C12	0.4810	0.3848	-20.000
C13-C15	0.6376	0.5101	-20.000
C16-C19	0.8143	0.6514	-20.000
C20-C56	1.1752	0.9402	-20.000
C57-C80	0.4987	0.3990	-20.000

Corr fac 4: Cpen (m^3/mol). Max adjustment: 50.00%.

	Before tuning	After tuning	%Adjustment
C7-C12	0.000	0.000	27.944
C13-C15	0.000	0.000	27.944
C16-C19	0.000	0.000	27.944
C20-C56	0.000	0.000	27.944
C57-C80	0.000	0.000	27.944

Sensitivity matrix:

Corr fac	d(Obj)/d(Corr fac)
1	2.19E+00
2	-9.78E-01
3	2.20E-01
4	-3.55E-01

Appendix G: MMP calculation for EOS model tuned with Coats and Smart (1986) tuning strategy

Jaubert F13 Oil EOS = PR Peneloux
Injection gas: Jaubert F13 Gas

Combined condensing and vaporizing drive MMP calculation at 377.55 K

Saturation pressure	171.3019	bara
Critical pressure	281.4551	bara
First contact misc pressure	349.9554	bara
Multi contact misc pressure	192.4819	bara
Drive type	39.84281	% Vaporizing

Lengths of key tie lines at MMP

Key tie line	Length
Oil tie line	0.299988
Crossover tie line 1	0.301969
Crossover tie line 2	0.019607
Crossover tie line 3	0.113678
Crossover tie line 4	0.171129
Crossover tie line 5	0.1848
Crossover tie line 6	0.217208
Crossover tie line 7	0.230456
Crossover tie line 8	0.250608
Crossover tie line 9	0.263167
Crossover tie line 10	0.31815
Crossover tie line 11	0.371964
Crossover tie line 12	0.421682
Gas tie line	0.544738

Appendix H: MMP calculation for EOS model tuned with Jessen and Stenby (2007) tuning strategy

Jaubert F13 Oil EOS = *PR Peneloux*
Injection gas: Jaubert F13 Gas

Combined condensing and vaporizing drive MMP calculation at 377.55 K

Saturation pressure	171.4724	bara
Critical pressure	235.0015	bara
First contact misc pressure	253.8578	bara
Multi contact misc pressure	166.3482	bara
Drive type	38.90582	% Vaporizing

Lengths of key tie lines at MMP

Key tie line	Length
Oil tie line	0.361387
Crossover tie line 1	0.368234
Crossover tie line 2	0.025591
Crossover tie line 3	0.102455
Crossover tie line 4	0.155051
Crossover tie line 5	0.167379
Crossover tie line 6	0.198581
Crossover tie line 7	0.210488
Crossover tie line 8	0.230856
Crossover tie line 9	0.24277
Crossover tie line 10	0.297572
Crossover tie line 11	0.351421
Crossover tie line 12	0.402854
Gas tie line	0.514715

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